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NASA Contractor Report 3291

Calculation of Water Drop Trajectories to and About Arbitrary Three-Dimensional Bodies in Potential Airflow

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CALCULATION OF WATER DROP TRAJECTORIES TO AND ABOUT ARBITRARY THREE-DIMENSIONAL BODIES IN POTENTIAL AIRFLOW

by Hillyer G. Norment
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SUMMARY

Computer programs are described by which trajectories of water drops can be calculated to and about three-dimensional, non-lifting bodies of arbitrary shape. External potential airflow about the body is computed; flow into (but not through) inlets also can be simulated. Calculations can be done for any atmospheric conditions and for any subsonic airspeed. Experimentally derived relations between Reynolds and Davies numbers for water drops of all sizes, from the smallest cloud droplets to large raindrops, are used to represent effects of aerodynamic drag on the particles during integration of the water drop equations of motion, and effects of gravity settling are included. A variable time step numerical integration method is used.

The surface of the three-dimensional body is approximated by plane quadrilateral panels, over each of which a uniform potential source is assumed to be distributed. Source densities and the resulting potential flow field are calculated by the Hess-Smith method.

The following seven codes are described:

1. A code used to debug and plot the body surface data.

2. A modified version of the Hess-Smith code which processes the body data and yields data required to compute flow velocities at arbitrary points in space.

3. A code that computes flow velocities at arrays of points in three-dimensional space.

4. A code that computes trajectories of water drops toward the body from arrays of initial points in space.

5. A code that computes water drop trajectories and water drop fluxes to arbitrary target points.

6. A code that computes water drop trajectories tangent to the body.

7. A code that produces stereo pair plots that include both the body and trajectories.

Code descriptions include operating instructions, card inputs and printouts for example problems, and listings of the FORTRAN codes.

Various tests of simulation accuracy are discussed, and accuracy is found to be acceptible. Trajectory results for flow around ellipsoids are compared with prior calculations and acceptable agreement is found. Results, again for flow about ellipsoids, are compared with experimental data and are found to be superior to prior calculations.

INTRODUCTION

With the development of practical numerical methods by which potential flow about arbitrary three-dimensional bodies can be calculated, along with development of efficient methods for integration of particle equations of motion, it has become possible to compute trajectories of particles suspended in a fluid to or about a complex body that is in motion relative to the fluid. Past applications have been to the study of mounting sites of hydrometeor measurement instruments on cloud physics research airplanes (refs. 1 - 8). In the future the methods are to be used to study aircraft icing, an application for which they are ideally suited, and it is in preparation for such work that this code documentation is undertaken.

We distinguish two major categories of codes: flow codes and trajectory codes. The flow codes process data that describe the three-dimensional body and compute the fluid flow field around that body.* The trajectory codes use the results of the flow codes to compute trajectories of particles to and about the body. For aircraft icing studies, the body is, of course, an aircraft, the fluid is air and the particles are water drops. Table 1 identifies and briefly describes the executive codes in the two categories, and Table 2 does the same for the subroutine and function codes.

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*It is immaterial whether we consider the fluid to be stationary and the body in motion, or vice versa, but it is expedient here to consider the body stationary and the fluid in motion.

TABLE 1

EXECUTIVE CODES

A. FLOW CODES

Code	Description
PBOXC	Processes and plots data which define the three-dimensional body. Used to debug and plot the body data.
BOXC	Processes three-dimensional body data and prepares and stores data to be used by SR FLOVEL to calculate flow velocities as needed during trajectory calculations.
FLOPNT	Computes and prints flow velocities at user-specified arrays of points in space.

B. TRAJECTORY CODES

Code	Description
ARYTRJ	Computes trajectories, which begin at user-specified arrays of points in space, to and/or about the body.
CONFAC	Computes trajectories from the free stream to user-specified points in space. Also computes particle concentration factors at user-specified points in space. (Concentration factor is ratio of particle flux at the target point to free stream particle flux.)
TANTRA	Computes trajectories tangent to the body which are initiated along user-specified lines in the free stream. (Tangent trajectories are those trajectories that barely miss intersection with the body.)
STEREO	Prepares stereo-pair plots of the body along with particle trajectories.

TABLE 2

SUBROUTINE AND FUNCTION CODES

A. FLOW CODES

Code	Called By	Description
AFORM	BOXC	Computes the induced velocity matrix, A_{ij} (ref. 9).
ATAPES	BOXC	Reads A_{ij} matrix from an appropriate tape.
DATPROS	INPUT	Translates, scales and rotates input body data before processing.
FLOVEL	TRAJECT CONFAC ARYTRJ FLOPNT	Returns flow velocity for a given point in space.
FLOWS	BOXC	Sets up non-uniform free stream flows.
HEADER	BOXC INPUT AFORM VFORM PRINT1	Writes a printout header.
INPUT	BOXC	Processes input body coordinate data into quadrilaterals. Produces the "first output" (ref. 9, sec. 9.4).
PATPROS	PINPUT	Translates, scales and rotates input body data before processing. Punches the translated, scaled and rotated data if so requested.
PEADER	PINPUT	Writes a printout header.
PICTUR	PBOXC	Plots the body surface data.
PINPUT	PBOXC	Processes input body coordinate data into quadrilaterals. Produces the "first output" (ref. 9, sec. 9.4).
PRINT1	BOXC	Computes and prints on-body velocities, and off-body velocities if so requested. Writes source strengths on unit 14 if so requested. Produces the "second output" (ref. 9., sec. 9.7).
SIGMA	BOXC	Solves linear equation matrix for surface source densities by the Seidel iterative method.
SOLVIT	BOXC	Solves linear equation matrix for surface source densities by the direct method.

TABLE 2, cont.

Code	Called By	Description
UNIFRM	FLOWS	Sets up uniform free stream flows.
VFORM	BOXC	Computes velocity components induced at each quadrilateral by all other quadrilaterals.
WTAP14	BOXC	Writes quadrilateral data needed for flow velocity computation onto unit 14 if so requested.

B. TRAJECTORY CODES

Code	Called By	Description
CDRR	PRFUN PARTCL	Given Reynolds number, returns Davies number for a sphere. Used for water drops for which Reynolds number is less than or equal to 200.
DVDQ	TRAJECT	Integrates particle equations of motion for each time step (ref. 11).
FALWAT	PARTCL	Returns still-air, terminal settling speed for a water drop. Uses equations of Beard (ref. 17).
IMPACT	TRAJECT	Used in runs under control of CONFAC to adjust trajectory initial y,z coordinates to avoid impact on the body on the next trajectory after impaction has occurred. This is a problem-specific subroutine.
MAP	CONFAC	Controls the iterative calculation of trajectories to a specified target point.
MATINV	MAP	Linear equation solver.
PARTCL	ARYTRJ CONFAC TANTRA	Reads particle specification data and returns still-air, terminal particle settling speed and other particle data as required for the particular type of particle. This is a particle type-specific code. The version provided here is for water drops.
POLYGON	CONFAC	Calculates area of a plane polygon of N vertices. Provides cross-sectional areas of particle flux tubes which are used to compute concentration factors.
PRFUN	TRAJECT	Given the particle Reynolds number, returns the factor which when multiplied by $\vec{v}_p - \vec{v}_a$ yields the first term on the right side of eq. (1). This is a particle type-specific function. The version provided here is for water drops.

TABLE 2, cont.

Code	Called By	Description
SETFLO	FLOPNT ARYTRJ CONFAC TANTRA	Reads BOXC output data stored on unit 14 that is required by SR FLOVEL for flow velocity calculations. If flow velocities are calculated by other than the Hess-Smith method, this code must be replaced with a dummy.
STRPNT	TANTRA	Specified a curve in three-dimensional space on which lie the initial points of all trajectories used in computing a tangent trajectory to the body. Also specifies coarse and fine step sizes to be used in traversing the curve in search of the tangent trajectory, and it steps along the curve to define new initial trajectory points under control of TANTRA. The version supplied here uses straight line curves.
TRAJECT	ARYTRJ TANTRA MAP	Computes particle trajectories. (See p. 38)
TRANSFM	CONFAC MAP	Transforms coordinate system from the "flow system" to the "flux tube system", or reverse. (See pp. 44, 45.)
WCDRR	PRFUN PARTCL	Given Reynolds number, returns Davies number for a water drop. Used for case where the Reynolds number is greater than 200.

METHODOLOGY

THREE-DIMENSIONAL FLOW

The code of Hess and Smith (refs. 9, 10) for calculation of non-lifting potential flow about arbitrary three-dimensional bodies is used. The code requires input of a digital description of the body surface. This consists of the coordinates of the corner points of a large number of quadrilaterals. (Examples of digital descriptions of portions of a C130 airplane are shown in Fig. 1.) Each quadrilateral panel is taken to be a uniform-distributed source. On the basis of the boundary condition that there be zero flux through the center of each panel, and given the direction of the free-stream flow, the code finds the source strengths of all panels by inversion of a large matrix that includes all possible panel interactions. The matrix is inverted only once for each airplane geometry, provided that the results are stored for future use.

This potential flow method works quite satisfactorily where the local Mach number does not exceed approximately one-half (ref. 10). By making simple adjustments to the calculations the method can be extended to higher Mach numbers as long as there are no supersonic regions in the real flow.

Particle trajectory calculations require flow velocities point-by-point along each trajectory. In calculating each flow velocity, contributions from all panels are summed. There are three algorithms for computing contributions: (1) for panels that are close to the calculation point, a detailed calculation is used that accounts for exact panel shape, (2) for panels at intermediate distances a multipole expansion is used, and (3) for remote panels a point source approximation is used. Mathematical details are found in references 9 and 10.

To perform these calculations, we have developed a subroutine (FLOVEL) that consists of various extracted and modified portions of the Hess-Smith code. This subroutine is generalized such that given geometrical properties, source strength and other data for every quadrilateral,

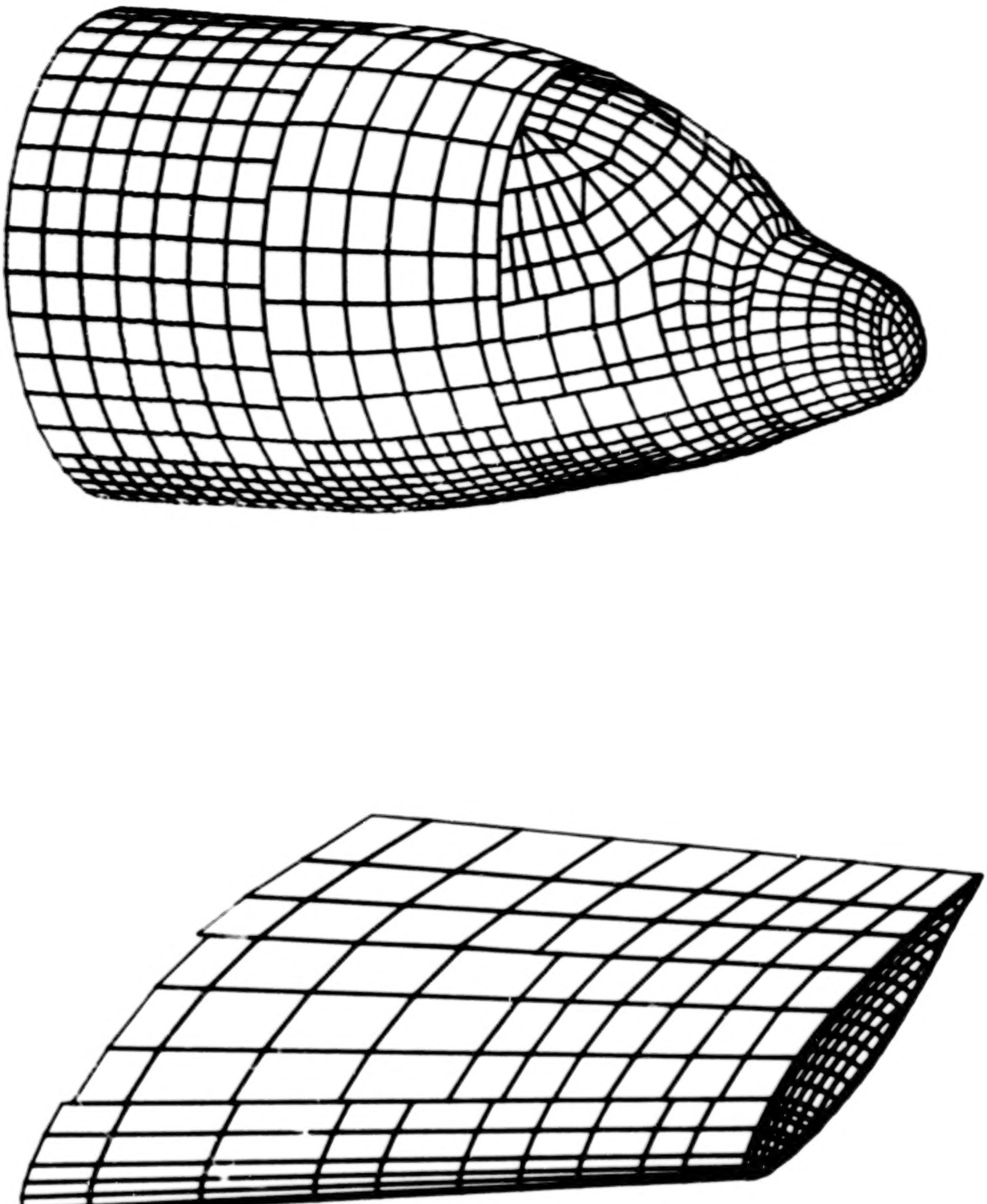


Figure 1. Digital descriptions of the forward fuselage and outer wing of a Lockheed C130E airplane.

it will provide the flow velocity for any specified point in space. It also checks each quadrilateral to determine if it has been penetrated by the particle.

Hess and Smith have evaluated the accuracy of their method for a variety of cases and have found excellent agreement with experiment (refs. 9 and 10). We have also done some evaluation studies (ref. 1), and in the Validation section below our prior work is summarized and results of some new studies of tangent trajectories to ellipsoids are presented and compared with prior work.

Of course accuracy also depends on the fineness of resolution of the panel description of the body, and naturally some compromise is called for. The smaller the panels the finer the resolution, and the fewer of them for which the most exacting of the three algorithms must be used. On the other hand, the number of panels increases inversely as the square of their linear size. In past studies on airplanes we have used the following criteria in setting up panel structures: For those parts of the airplane traversed by particle trajectories, we try to keep the panel edges between 6" to 8" in length. Where allowed by simplicity of surface shape, remote panels can be larger. Remote downstream complexities of shape are ignored. The cylindrical portion of a fuselage is extended to approximately five times the length of the nose section, as recommended by Hess and Smith (ref. 10).

For a particular computer, time required for trajectory calculation is largely dependent on the number of velocities required. On the CDC 6600 computer, one velocity calculation requires on the order of 0.15 second for a typical problem. The number of velocities required per trajectory varies from about 60 to 300. A typical number of trajectories required is 25. Thus, computing time, even on a large computer, can be considerable. Computing times required on the UNIVAC 1100 are included here for each of the test problems. (See p. 60.)

Though the flow codes retain additional capabilities, for the calculations described here we require the following:

1. A unit free stream speed in the direction of the positive x axis.

2. All velocities are normalized and scaled to be consistent with the unit free stream speed.

3. All distances are normalized by dividing by a user-specified characteristic dimension of the body.

Body coordinates may be recorded in any convenient units and can be appropriately scaled and translated prior to processing via use of SR's PATPROS and DATPROS. These subroutines also allow rotation of the body about the y axis to adjust angle of attack.

PARTICLE TRAJECTORY CALCULATION

We assume that the bulk air flow is not perturbed by the particles. Moreover, since particle density is large compared to that of air, we can neglect buoyancy and inertial reaction of the fluid to obtain the three-dimensional, normalized equation

$$\frac{d\vec{v}_p}{d\tau} = \frac{1}{N_F}\left[\frac{1}{v_s}\left(\vec{v}_a - \vec{v}_p\right)\frac{N_D N_{R,s}}{N_{D,s} N_R} - \vec{k}\right] \quad . \qquad (1)$$

Non-dimensional quantities are:

$\vec{v}_p$, $\vec{v}_a$	particle and air velocities
v_s	still-air, terminal settling speed of the particle
$\vec{k}$	unit vector in the z (upward) direction
τ	time

$N_D = C_D N_R^2$ Davies number

$N_F = V^2/(Lg)$ Froude number

$N_R = \frac{\rho\delta}{\eta} |\vec{v}_a - \vec{v}_p| V$ Reynolds number

Dimensioned quantities are:

δ particle diameter

ρ air density

η air viscosity

g gravity acceleration constant

V free stream airspeed

L a characteristic dimension of the body

Here length is normalized by dividing by L, velocity by V and time by L/V. $N_{D,s}$ and $N_{R,s}$ are for still-air, terminal particle settling.

We initiate the calculation far enough upstream to be essentially beyond the influence of the body where we can take $\vec{v}_p = -\vec{k}v_s$. We compute $\vec{v}_a$ at the initial point, calculate N_R from these data, calculate N_D from N_R using the relations discussed in the next section, and proceed straightforwardly with a numerical integration of eq. (1). The integration is done via use of the code DVDQ of Krogh (ref. 11). This code uses an Adams-type predictor - corrector algorithm with variable time step. It also tests for computational stability and loss of accuracy via roundoff error. It was tested by Hull, et al., (ref. 12) along with a number of other codes and found to be most efficient in terms of numbers of function evaluations (flow velocities) required.

AERODYNAMIC DRAG OF WATER DROPS

Davies (ref. 13) shows that still-air terminal settling of spheres can be generalized in terms of the dimensionless numbers $N_{R,s}$ and $N_{D,s}$. Over the range from the smallest spheres, which settle under viscous flow conditions and obey Stokes law, to spheres much larger than of interest here, and for any Newtonian fluid, a reproducible single-valued relationship between $N_{R,s}$ and $N_{D,s}$ exists. Furthermore, $N_{D,s}$ is independent of settling speed, being a function of fluid and sphere properties only; thus for given sphere and fluid, $N_{R,s}$ and hence V_s can be calculated. Polynomials by which $N_{R,s}$ can be computed as a function of $N_{D,s}$ were derived by Davies from a composite of many sets of experimental data.

Since the work of Davies it has been found repeatedly that this treatment is applicable to particles of other shapes, providing settling is steady and particle orientation is stable.

For the trajectory calculations required here, the problem must be turned around. In addition to gravity settling, there is a particle velocity component (relative to air) caused by the disturbance of the passing airplane. At any time step in the numerical integration of eq. (1), $\vec{v}_a - \vec{v}_p$ (and hence N_R) is known, and N_D must be determined. For viscous motion (i.e., Stokes flow, where $N_R < 1$) $N_D = 24\ N_R$ and eq. (1) can be integrated without question. However, for larger N_R the steady-state drag data determined experimentally for terminal settling must be used to compute accelerative particle motion.

Experimental measurements by Keim (ref. 14) and a theoretical analysis by Crowe, et al. (ref. 15) indicate that if the acceleration modulus,

$$N_A = \delta\left|\frac{dV_p}{dt}\right|/V_p^2 ,$$

is smaller than about 10^{-2}, steady-state drag coefficients can be used without significant error to compute accelerative motion. N_A has never been found to exceed 10^{-2} in our trajectory calculations.

For water drops small enough to be essentially spherical ($N_R \leq 200$) we calculate N_D from a polynomial function in N_R derived from Davies data (ref. 13). (Function CDRR) For larger drops ($N_R > 200$), which have a flattened, non-spherical shape, we calculate N_D from polynomials in N_R derived from the water drop data of Gunn and Kinser (ref. 16). (Function WCDRR).

Still-air, terminal settling speeds for water drops are computed via use of Beard's equations (ref. 17). (SR FALWAT)

Water drops of any size, from submicron to the breakup size at about 8000 μm diameter, can be handled by these methods. However, the user should be aware that computation time goes up as droplet diameter goes down, and the time required for drops of diameter 1 μm or less may be large.

We have also developed aerodynamic drag relationships from observed settling data for various forms of ice crystals and have used these to study trajectories of ice to and around various airplanes (refs. 1, 2, 5, 7), though these are not included here.

FLOW CODE DESCRIPTIONS

PROGRAM PBOXC

General Discussion

This program is derived from the Douglas Aircraft Company code BOXC which was developed by Hess and Smith (ref. 9). It processes and produces CALCOMP plots of the three-dimensional body surface description data and is used primarily to debug these data. Processing and printing go as far as the "first output" (ref. 9, sec. 9.4). A secondary use is to store the body surface data such that it can be retrieved later and used by PGM STEREO to plot the body along with trajectories stored by one of the trajectory codes.

The surface of a general three-dimensional body is defined in terms of "rows" and "columns", the so-called m and n lines, of coordinates of points on the surface as described below. The m and n lines of points are combined by the code to form quadrilateral elements, or panels, such that when considered together they represent a reasonable approximation to the surface. (For example see Figs. 1 and 8.) Adjacent panels should be contiguous, or as nearly contiguous as possible. The data for general bodies may be scaled and translated in the three coordinate directions, and rotated about the y axis prior to processing.

The code also has the capability of generating ellipsoids of prolate, oblate or general shape with the only restriction being that their major and minor axes lie on the coordinate axes.

When the user elects to prepare plots of the body, the code automatically prepares a number of plots, each from a unique viewing angle, the number varying according to symmetry. For an asymmetric body fourteen plots are prepared. These consist of the six views from both directions along each coordinate axis, and the eight plots from 45 degree angles in each octant.

For a body with one plane of symmetry nine plots are prepared, for two symmetry planes six plots, and for three planes four plots. The user is urged to make liberal use of the plots to find errors in the body data.

Symmetry Planes

Up to three reflection planes may be specified, though only the first two are used in PBOXC for plotting. The surface descriptions for general bodies and ellipsoids are reflected across these planes. The number of symmetry planes is specified by parameter NSYM which has allowed values of 0, 1, 2, 3. The symmetry planes, in order of their application to the data, are:

Order of Application	Symmetry Plane
1	y = 0
2	z = 0
3	x = 0

For example, if NSYM = 1, for each point with coordinates (x,y,z), another point with coordinates (x, -y, z) is created. If NSYM = 2, for each point with coordinates x, y, z, three additional points with coordinates (x, -y, z), (x, -y, -z) and (x, y, -z) are created. If NSYM = 3, seven additional points are created.

Only the primary data points should be input. If reflected as well as primary data are input, the flow calculations will be in error.

Surface Description Data For General Bodies (IFLAG = 0)

The user must examine the body, or drawings of it, and devise a layout plan for subdividing its surface into sections that are compatible with the requirements of m line, n line surface point input while providing panels of

appropriate size which cover the surface without leaving gaps or introducing unwanted discontinuities. Also a coordinate system must be established, but this can be manipulated at processing time by use of the scaling and translation capability of the code.

The important thing is to understand the requirements of the m and n line input. Here we give a brief summary of the requirements; the user is encouraged to carefully study sec. 9.1 of reference 9 to obtain a thorough understanding of them.

Points which define the corners of the quadrilateral panels are labeled with integers m and n which identify hypothetical "rows" and "columns" on which they lie. The integers m and n are not input to the computer; they are used for data organization and sequencing only.

To ensure a proper computation, the rows and columns must be organized by the following rule: <u>If an observer is located in the flow and is oriented so that locally he sees points on the surface with m values increasing upward, he must also see n values increasing toward the right</u>.

A surface may be subdivided into sections, each of which must be independent. That is, all quadrilaterals in each section must be closed. Where an edge of a section is contiguous with another, the input for each section must define the common edge, though they need not use the same points on the edge.

Figure 2 illustrates a surface description that is subdivided into four sections. Note how the sectioning can be used to change resolution or to deal with structural complexities.

Coordinates are punched into cards, one point per card; also in each card is punched the integer parameter STAT which is used to identify the m,n status of each point. All points in a section are ordered in the sequence (m,n):

(1,1), (2,1), (3,1),..., (1,2), (2,2), (3,2),...(1,3), (2,3), (3,3),...

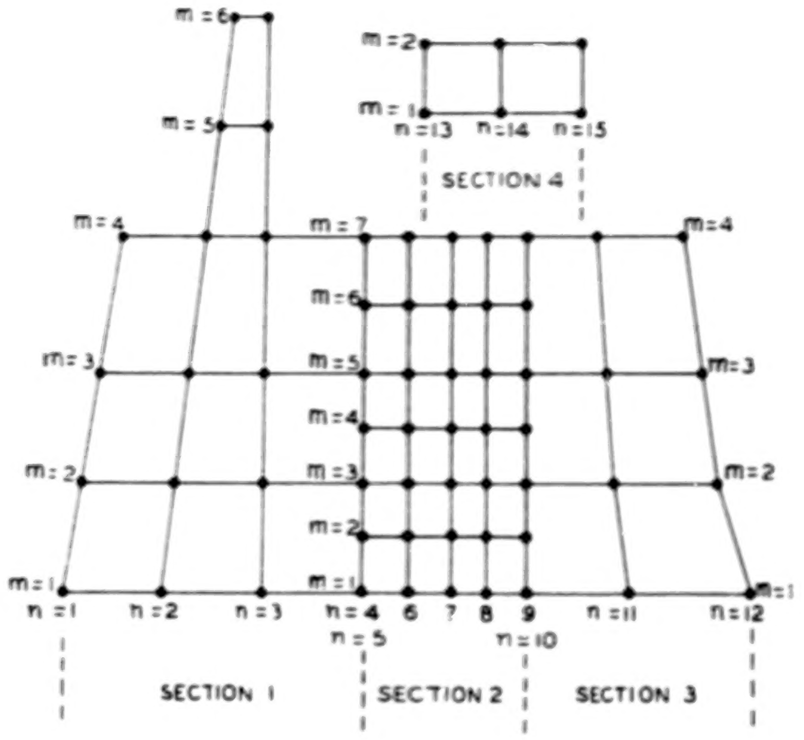


Figure 2. Plan view of the input points on a body divided into sections. (From ref. 9)

The STAT parameters are as follows for each section:

(m,n)	STAT
(1,1)	2
(1,n≠1)	1
all others	0 or blank

For the last card of the last section, STAT = 3.

Input order of sections is immaterial, but within sections, the data must be ordered according to the underlined rule given above.

Surface Description Data for Ellipsoids (IFLAG = 2 or 3)

Ellipsoids are generated by specifying the semi-axis lengths B and C (A = 1 always), and by specifying the numbers of "latitudinal" and "longitudinal" element divisions (Fig. 3), NLM1 and MMIN respectively.

There are two modes for specification:

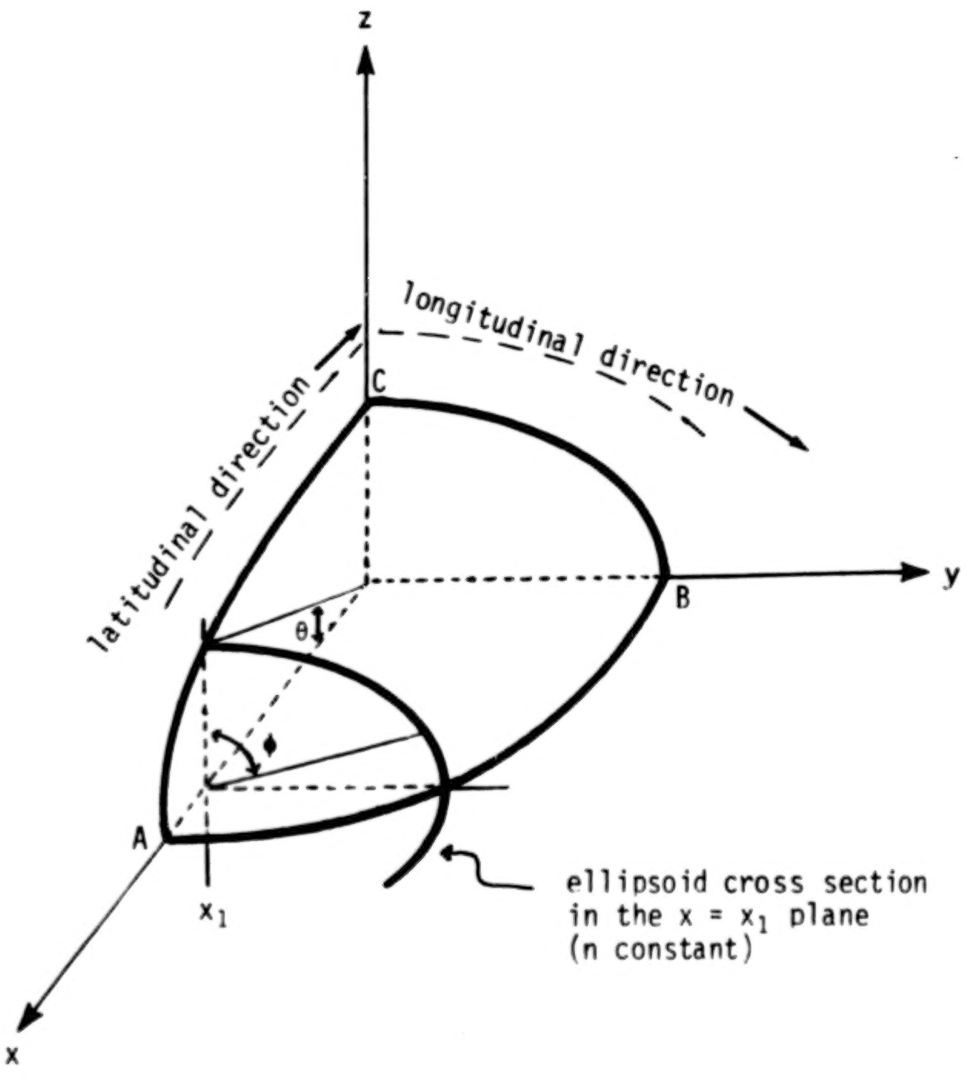
Mode 1. IFLAG = 1, NSYM = 3

All three symmetry planes are used and NLM1 and MMIN are specified for one octant only. Element increments are computed for NLM1 and MMIN equal increments in angles θ and ϕ (Fig. 3).

Mode 2. IFLAG = 2, NSYM = 2

Only two symmetry planes are used, and (x, z) values in the $y = 0$ plane must be input for $-1 \leq x \leq 1$, beginning at (1,0) and proceeding to (-1,0) for either all positive z or all negative z (i.e., for 180° in angle θ). (The code automatically ensures that the "underlined" input rule is obeyed.) Thus, NLM1 must be specified for the entire x axis, but MMIN is for one octant only as for the other option, and element increments in the "longitudinal" direction are created at equal increments of the angle ϕ.

Body surface data for generated ellipsoids cannot be plotted nor can the data be translated, scaled, and rotated by subroutine PATPROS or DATPROS.



θ is in the $y = 0$ plane

ϕ is in the $x = x_1$ plane

n lines run in the latitudinal direction from $\theta = 0$ to $\theta = \pi$

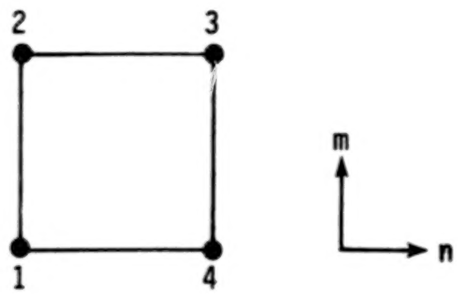
m lines run in the longitudinal direction from $\phi = 0$ to $\phi = 2\pi$

Figure 3. Definition of angles θ and ϕ, and m and n line directions used by PBOXC and BOXC for generation of ellipsoids.

Printed Output

The printed output is the result of the first stage of surface data processing (ref. 9, sec. 9.4). For each quadrilateral panel on the surface it consists of:

1. Coordinates (X,Y,Z) of the four points on a quadrilateral in the order



around the quadrilateral.

2. Components (NX,NY,NZ) of the unit normal vector to the plane of the quadrilateral. This vector should point toward the exterior of the body rather than toward its interior. If it points in the wrong direction the data have been input in violation of the "underlined rule" on p. 17, and the data must be reordered.

3. Coordinates (NPX,NPY,NPZ) of the quadrilateral null point (ref. 9., sec. 9.3).

4. The common projection distance (D) of the four input points into the plane of the quadrilateral. (The four points from which a plane quadrilateral is formed do not in general, and need not, lie exactly in a plane.)

5. The maximum diagonal length (T) of the quadrilateral.

6. The area (A) of the quadrilateral.

Additional output appears for certain abnormal quadrilaterals. If the integer 1 or 2 appears at the far right of the page, they indicate the following conditions:

Integer 1. The null point point was found to lie outside of the quadrilateral. The coordinates listed are for the quadrilateral centroid.

Integer 2. The iterative procedure used to determine the null point did not converge and thus the null point is only approximate

(ref. 9, sec. 9.3).

Subroutines Required

PINPUT, PICTURE, PEADER, PATPROS, plotting subroutines.

External Storage Units

Units 5 and 6 are the system input and print units respectively.

Unit 8 temporary storage.

Unit 9 storage for surface data to be used later for plotting by PGM STEREO.

PBOXC Card Input

Card No.	Variables and Format	Description	
1	HEDR(15), IFLAG, NSYM, KMACH, KASE, (15A4, I1, 10X, I1, 1X, I1, 2X, A4)	HEDR (Cols. 1-60)	Hollerith run identification
		IFLAG (Col. 61)	Body surface description input control
		IFLAG = 0	Input data for a general, three-dimensional body (See pp. 16 ff.)
		IFLAG = 1	Generate an ellipsoid using the mode 1 option, with three reflection planes. (See p. 19.) Be sure that NSYM = 3.
		IFLAG = 2	Generate an ellipsoid using the mode 2 option, with two reflection planes, and input x,z coordinates for the ellipsoid via cards no. 5C. (See p. 19.) Be sure that NSYM = 2.
		NSYM (Col. 72)	Number of data reflection planes. Limited to values 0,1,2,3. (See p. 16.)
		KMACH (Col. 74)	A non-zero value indicates that a Mach number is to be read via card no. 2. (See p. 26.)
		KASE (Cols. 77-80)	Hollerith body identification.
2	MACH, (F10.6)	Mach number	This card is input only if KMACH ≠ 0 on card 1. (See p. 26.)
3	IPROS, IPUNCH, IPRNT, IPICT, ICRT, (5L1)	Logical variables which cause the following if true:	
		IPROS	Body surface data for a general body are to be translated, scaled and rotated about the y axis before processing, and card 4 is to be input.
		IPUNCH	Body surface data are copied to the system punch unit after translating, scaling and rotating about the y axis.
		IPRNT	Body surface data are processed and printed up to the "first output". (See p. 21 and ref. 9, sec. 9.4.)
		IPICT	Body surface data for a general body are plotted.
		ICRT	Plotting is via CRT. If ICRT is false, plotting is via pen and ink.
4.	ANGLE, XSCALE, YSCALE, ZSCALE, XTRANS, YTRANS, ZTRANS, (7F10.0)	This card is input only if IPROS (card 3) is true.	
		ANGLE	Angle (degrees) that the body is rotated about the y axis. A positive value causes a counterclockwise rotation from the aspect of a viewer looking down the positive y axis toward the origin. (Note: For a nose-up airplane angle of attack, ANGLE is negative.)
		XSCALE, YSCALE, ZSCALE	Scale factors to be applied to surface point x, y and z coordinates respectively after translation. Default values are unity.
		XTRANS, YTRANS, ZTRANS	Translations to be applied to surface point x, y and z coordinates before scaling.

- -

Card No.	Variables and Format	Description	
5A	X,Y,Z,STAT, XX, YY, ZZ, STATT, (3F10.0, I2/3F10.0,I2)	Cards 5A apply to general bodies (IFLAG = 0, see pp. 16 ff).	
		X,Y,Z and XX, YY, ZZ	Are coordinates of points used to define the body surface.
		STAT STATT (Col. 32)	Are point status integers. Allowed values are 0, 1, 2, 3. The meanings of these values are: 0 This point is on the same n line as the last point 1 This point starts a new n line 2 This point starts a new section 3 This is the last point in the input.

Card No.	Variables and Formats	Description
5A cont.		Note: For the last coordinate card STAT or STATT = 3. A blank card should follow this if there is an odd number of body surface points.
5B	NLM1, MMIN, B, C, (2I5, 2F10.5)	Card 5B applies to generated ellipsoids (IFLAG > 0) NLM1 Number of "latitudinal" element divisions MMIN Number of "longitudinal" element divisions B y semi-axis of the ellipse C z semi-axis of the ellipse (See p. 19 Modes 1 and 2, and Fig. 3.)
5C	x_1, z_1, x_2, z_2, ...x_{NLM1+1}, z_{NLM1+1} (8F10.0) . . .	Cards 5C apply to generated ellipsoids for which the x,z coordinates are input (IFLAG = 2, NSYM = 2). (x_i, z_i) are coordinates in the y = 0 plane, beginning at (1,0) and proceeding to (-1,0), that define the "latitudinal" element subdivisions. (See p. 19 Mode 2, and Fig. 3.)
6,7	LINE1, LINE2, (7A6/7A6)	Cards 6 and 7 are read only if ICRT is true (card 3). These are two lines of 42 columns each of Hollerith labeling for a microfiche film.

PROGRAM BOXC

General Discussion

Program BOXC is the Hess-Smith code for calculation of potential flow about arbitrary, three-dimensional, non-lifting bodies as described in ref. 9, with the following exceptions:

1. Overlay, common and subroutine argument structures have been changed to accommodate the code to the CDC 6600 and UNIVAC 1100/42 computers.

2. SR WTAP14 has been added to store on external unit 14 all data needed by the trajectory codes for flow velocity calculations.

3. A provision has been added to allow a group of surface elements to leak inward a specified fraction of the free stream flow. This is used to simulate effects on external flow of air flow into inlet aperatures.

4. A provision has been added to scale, translate and rotate surface point coordinates for general bodies before they are processed. (SR DATPROS)

To understand the theory and details of the calculations, the user must study reference 9.

The code has the capability to compute flow about the body for the free stream vector along each of the three axial directions. For nonsymmetrical bodies the capability extends to any free stream direction, and for bodies with one plane of symmetry, which must be the y = 0 plane, to any direction in the y = 0 plane (ref. 9, sec. 9.56). However, these general capabilities have not been used in the past, and furthermore, the trajectory codes and other important features of the flow calculations which are discussed below assume that the free stream vector is in the direction of the positive x axis. Changes of body orientation and/or location relative to the flow coordinate system are accomplished via use of SR DATPRO, which in its

present form also is designed to allow for arbitrary specification of airplane angle-of-attack. In any case the free stream flow speed must be unity. The card input instructions below specify unit onset flow in the positive x direction.

Use and application of symmetry planes as well as preparation of body surface description data are the same as for PGM PBOXC.

Up to 1000 quadrilaterals can be accommodated for description of the basic body surface, before multiplication by symmetry plane reflection.

Compressibility Effects

According to Hess and Smith (ref. 10, pp. 7 and 35) their method works satisfactorily where the local Mach number does not exceed approximately one-half. For higher Mach numbers the Gothert transformation (ref. 18) is applied as follows:

1. All distances in the free-stream direction, that is the x direction, are scaled by dividing by $\beta = \sqrt{1 - M^2}$, where M is free stream Mach number.

2. Perturbation velocities computed at the scaled distances are themselves scaled by dividing by β for the y and z components, and by dividing by β^2 for the x component.

If the Gothert transformation is to be applied, the parameter KMACH (card 1) is given a value greater than zero, and the Mach number is input via card 5.

Flow Inlets

We have added a feature to the code (in SR UNIFRM) to allow simulation of flow up to the aperture of a flow inlet. The code cannot handle internal flows.

The aperture is represented by quadrilateral panels in the same manner as the body surface. To illustrate this, Fig. 4 shows the panelling of the orifice in the tip of the intake tube of a cloud water meter, the EWER, which is mounted under the wing of a C130 research airplane (ref. 7). Inlet aperture panel coordinates must be the first in the deck of surface point cards (cards 6A).

Input card no. 4 contains the number of aperature quadrilaterals and also the fraction of the free-stream flow speed that is "leaked" through the apertures. This leakage is taken to be the same for each aperture quadrilateral. If there is no flow inlet, card 4 is blank.

Off-Body Points

The code provides for computation of flow velocities at off-body points. If the parameter NOFF (card 1) is given a value greater than zero, coordinates of the off-body points are input following the surface points via the same format. The only status flag (STAT or STATT) required is 3 for the final point.

Printed Output

The printed output consists of two main parts: the first is the result of preliminary processing of the surface description data which yields "the first output" (ref. 9, sec. 9.4) described above on p. 21. The second output contains the final results and consists of the following for each quadrilateral (ref. 9, sec. 9.7):

1. Null point coordinates (NX, NY, NZ) (ref. 9, sec. 9.3).

2. Velocity magnitude (VT) at the null point.

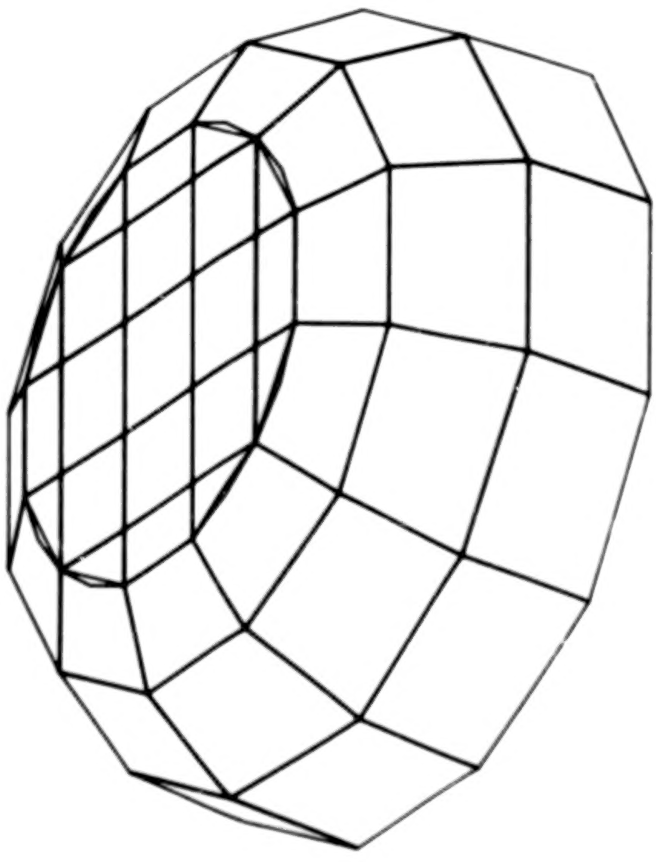


Figure 4. Computer plot of tip and orifice of a EWER cloud water content meter probe (ref. 7).

3. Square of the null point velocity magnitude (VTSQ).

4. Pressure coefficient (CP) (ref. 9, eq. (137)).

5. Null point velocity components (VX, VY, VZ).

6. Direction cosines of the null point velocity (DCX, DCY, DCZ).

7. Unit normal vector to the plane of the quadrilateral (NX, NY, NZ).

8. Component of velocity normal to the quadrilateral plane at the null point (VN). (Note: VN should be essentially zero unless the quadrilateral is part of a flow inlet (see p. 26), in which case it should equal the input free-stream flow fraction.)

9. Source strength of the quadrilateral (SIG).

Unit 14 Output

If parameter KTP14 is unity (card 1), the following data are stored on external unit 14 (in binary format) for use later by SR FLOVEL in calculating flow velocities at arbitrary points in space:

Body identification, KASE (see card 1), number of symmetry planes, NSYM, the number of quadrilaterals, NQUAD, in the basic body unit (i.e., before multiplication by symmetry plane reflections), free-stream Mach number, MACH, and $(1 - \text{MACH}^2)^{-\frac{1}{2}}$.

For each quadrilateral is stored the "twenty-eight quantities" (ref. 9, sec. 9.51), plus the distances between quadrilateral points 1 and 2, 2 and 3, 3 and 4, and 4 and 1. (See p. 21.)

Overlay Structure and Subroutines Required

To conserve storage the program is run with the overlay structure shown in Fig. 5, which also identifies the subroutines required.

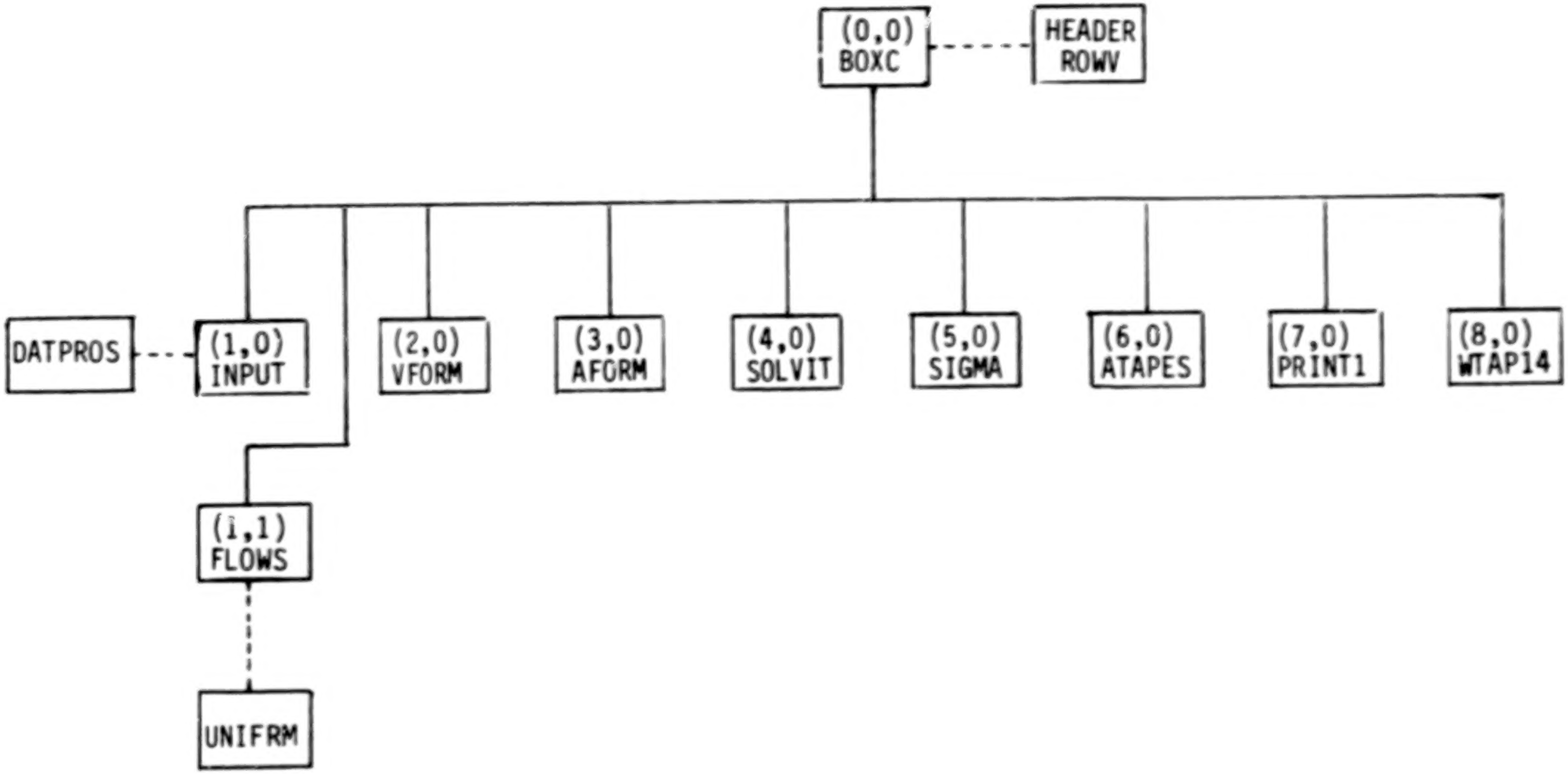


Figure 5. Overlay structure for program BOXC. The integer pairs (i,j) indicate the primary, i, and secondary, j, overlay levels.

External Storage Units

Units 5 and 6 are the system input and print units. Unit 14 contains the data to be used by SR FLOVEL to compute flow velocities at arbitrary points in space. The following units are used for temporary storage: 1, 3, 4, 8, 9, 10, 11, 12, 13.

BOXC Card Input

Card No.	Variables and Format	Description	
1	HEDR(15), IFLAG, LIST, AFLOW, BFLOW, CFLOW, ISIG, IPRS, MPR, NCODE, NNON, NSYM, NOFF, KMACH, KTP14, KASE, (15A4, 2I1, 3L1, 4I1, I2, 4I1, 1X, A4)	HEDR (cols. 1-60)	Hollerith run identification
		IFLAG (col. 61)	Body surface description input control. Same as for card 1 of PBOXC. (See pp. 16ff.)
		LIST (col. 62)	A value of zero (or blank) causes full execution. Otherwise, calculation is stopped after the "first output". (See p. 21.)
		AFLOW, BFLOW, CFLOW (Cols. 63, 64, 65)	Logical parameters which specify the free-stream flow axis. These parameters should be T,F,F respectively.
		ISIG (Col. 66)	Always zero or blank.
		IPRS (Col. 67)	Always zero or blank.
		MPR (Col. 68)	Normal value is zero or blank. Non-zero values cause printout of the following matrices (ref. 9): 1 print V_{ij} 2 print A_{ij} 3 print V_{ij} and A_{ij} (output is voluminous for large cases)
		NCODE (Col. 69)	Always zero or blank.
		NNON (Cols. 70,71)	Always zero or blank.
		NSYM (Col. 72)	Number of symmetry planes. Same as for card 1 of PBOXC. (See p. 16.)
		NOFF (Col. 73)	Number of off-body points for which velocity calculations are to be calculated. (See cards 7)
		KMACH (Col. 74)	A non-zero value indicates that a Mach number is to be read via card 5.
		KTP14 (Col. 75)	If given a value of one, the unit 14 output is prepared. (See p. 29)
		KASE (Cols. 77-80)	Hollerith body identification.
2	IPROS, (L1)	If true, body surface data for a general body (IFLAG = 0) are to be translated, scaled, and rotated about the y axis before processing, and card 3 is to be input.	
3	ANGLE, XSCALE, YSCALE, ZSCALE, XTRANS, YTRANS, ZTRANS, (7F10.0)	This card is input only if IPROS (card 2) is true. Same as card 4 of PBOXC.	
4	LEAK, FRACT, (I4, F10.0)	LEAK	Number of quadrilaterals used to define a flow inlet in the body.
		FRACT	Fraction of the free-stream air speed that passes through the null point of each inlet quadrilateral.
		If there is no flow inlet, input a blank card. (Note: the inlet quadrilateral data (cards 6A) must be the first body data input.) (See p. 26)	

BOXC Card Input, cont.

Card No.	Variable and Format	Description
5	MACH, (F10.6)	Free-stream Mach number. This card is input only if parameter KMACH (card 1) is non-zero.
6A	X, Y, Z, STAT, XX, YY, ZZ, STATT, (3F10.0, I2/3F10.0, I2) . .	Cards 6A apply to general bodies (IFLAG = 0) Coordinates and status flags for points used to describe the body surface. Same as cards 5A of PBOXC. (See pp. 16 ff)
6B	NLM1, MMIN, B, C, (2I5, 2F10.5)	Card 6B applies to generated ellipsoids (IFLAG > 0). Same as card 5B of PBOXC. (See p. 19)
6C	$x_1, z_1, x_2, z_2, \ldots.$ x_{NLM1+1}, z_{NLM1+1} (8F10.0).	Cards 6C apply to generated ellipsoids for which the x,z coordinates are input. (IFLAG = 2, NSYM = 2). Same as cards 5C of PBOXC. (See p. 19)
7	X, Y, Z, STAT, XX, YY, ZZ, STATT, (3F10.0, I2/3F10.0, I2)	Off-body points for which flow velocities are to be calculated. Cards 7 are input only if NOFF (card 1) is greater than zero. STAT or STATT for the last point must be 3. If there are an odd number of points, the deck of off-body point cards should be terminated with a blank card.

SUBROUTINE FLOVEL

Given the coordinates of a point in space (XNPP, YNPP, ZNPP) and the current time step, H, used in the integration of the particle equations of motion, SR FLOVEL returns the flow velocity components (VXPP, VYPP, VZPP) at that point, and an indicator, INBODY, of whether the body surface has been penetrated. INBODY = 0 if the point is exterior to the body, but INBODY = 1 if it is detected to be inside the body.

The discussion to follow assumes that a Hess-Smith (ref. 9) flow field is being considered. However, if the user wishes to compute flow by use of some other method, for example, flow about an ellipsoid via an analytical equation, he may replace FLOVEL by a subroutine of his own design.*

SR FLOVEL is based mainly on the Hess-Smith subroutine VFORM, with modifications required to include the quadrilateral source strengths, and to set the INBODY parameter. Application of the source strengths (i.e., σ values) is straightforward, as indicated by eq. (140) of reference 9, and needs no further discussion. Determination of whether or not the body has been penetrated is discussed next.

FLOVEL calculates and sums velocities induced at the specified point by each quadrilateral. Three modes of induced velocity calculation are used (ref. 9, sec. 9.52): 1. where the distance between the point and the quadrilateral is sufficiently large the quadrilateral is approximated by a simple point source, 2. for intermediate distances the quadrilateral is approximated by a point source plus a point quadrupole, and 3. for short distances an exact calculation is used. For each quadrilateral for which

*In the trajectory codes a call of SR SETFLO precedes the first call of FLOVEL. SETFLO reads the data stored on unit 14 by PGM BOXC (see p. 29), which data are required by FLOVEL for calculation of a Hess-Smith flow velocity, and puts these data into COMMON storage. If a user-designed version of FLOVEL is used, SETFLO must be replaced by a dummy subroutine.

the exact calculation is required the following tests are made in sequence, and if any one is satisfied, penetration is taken not to have occurred:

1. The vector of separation between the point and the center of the quadrilateral is projected onto the normal vector to the quadrilateral, and the sign of the projection is checked to see if the point is on the exterior side of the quadrilateral.

2. If the distance of the point to the center of the quadrilateral is greater than one-half of the maximum quadrilateral diagonal, penetration of the quadrilateral has not occurred.

3. If the absolute value of the projection calculated in test 1 is greater than the time step, H, penetration of the quadrilateral has not occurred.

For test 3 we assume that the maximum particle speed is about unity, so that the maximum distance a particle can travel in one time step is roughly H.

These tests are applicable only during trajectory calculations when the particle is advancing by small steps such that if penetration occurs the particle will be close to the point of penetration when the tests are made. The tests will not give a penetration indication for interior points that are not close to the body surface.

PROGRAM FLOPNT

General Description

This program computes flow velocities at an array of points in three-dimensional space. The array is oriented parallel with the three coordinate axes. Flow velocities are computed by SR FLOVEL, which uses data that, for example, are prepared by program BOXC for flow about an arbitrary three-dimensional body.

Initial coordinates, array increment values along the three coordinate directions and the number of increments desired along each direction (including the initial point) are input. Also input are integers M(3) which control the order of incrementing along three axes. For example, suppose M(1) = 3, M(2) = 1, M(3) = 2:

1. The x and z coordinates are held fixed while y is incremented over its range.

2. y is returned to its initial value, z is incremented once, and y is incremented over its range.

3. This is repeated until z covers its complete range.

4. z is returned to its initial value, x is incremented once, and y is incremented over its complete range.

5. etc.

The printed output is self-explanatory and consists of point coordinates, velocity components and speed.

If data prepared by BOXC are used, SR SETFLO reads these data from unit 14; units 5 and 6 are used for input and printing, respectively.

Subroutines called are: SETFLO, FLOVEL.

FLOPNT Card Input

Card No.	Variables and Format	Description
1	KASE, (A4)	Body identification. Read by SR SETFLO, and must be identical to the identification on card 1 of BOXC.
2	HOLL(18), (18A4)	Run identification.
3	M(3), (3I2)	Coordinate incrementation sequence control. (See discussion above.)
4	X(I), D(I), N(I); I = 1 (2E10.0, I4)	X(1) initial x coordinate (dimensionless) D(1) x coordinate increment (dimensionless) N(1) number of increments desired in the x direction (including initial value).
5	X(I), D(I), N(I); I = 2	Same as card 4 but for the y axis.
6	X(I), D(I), N(I); I = 3	Same as card 4 but for the z axis.
3'	Cards 3 - 6 are repeated for another array.	
.	.	
.	.	
.	.	
.	.	
.	.	
3	Blank card	A blank card 3 terminates the run.

TRAJECTORY CODE DESCRIPTIONS

GENERAL UTILITY CODES

Subroutine PARTCL

Subroutine PARTCL is called by all three of the executive trajectory codes (Table 1B) to input particle specification data and compute still-air, terminal particle settling speed and other data depending on particle type. This is a particle type - specific code, the version used here being for water drops. It calls SR FALWAT.

Subroutine TRAJECT

Trajectories are calculated by SR TRAJECT with the assistance of: SR DVDQ, the numerical integrator code, SR FLOVEL and the functions PRFUN and IMPACT. It also stores trajectory point coordinates at user-specified (normalized) time intervals (TPRINT) in arrays XPLOT(60), YPLOT(60), ZPLOT(60), providing logical parameter IPLOT is specified as true.

Function PRFUN

Function PRFUN is a particle type - specific code which is called by TRAJEC to provide the N_D - N_R relation used in calculating the particle equations of motion (eq. (1)). Actually, through use of the pre-calculated quantity COF (= $N_{D,s} v_s N_F / N_{R,s}$), PRFUN returns the factor on the first term on the right side of eq. (1) which when multiplied by $\vec{v}_a - \vec{v}_p$ yields the particle equation of motion. The version of PRFUN used here is for water drops, and it calls functions CDRR and WCDRR.

Subroutine IMPACT

Subroutine IMPACT is called by TRAJECT following penetration of a particle into the body. When used with CONFAC, IMPACT adjusts trajectory initial y and z coordinates such as to avoid impaction by the next trajectory (see p. 44); accordingly IMPACT is a problem-specific code. No such adjustment is required for cases run under control of ARYTRJ and TANTRA*, so that a dummy version of IMPACT is used.

Subroutine SETFLO

Subroutine SETFLO reads data prepared by PGM BOXC from external unit 14. These data are required by SR FLOVEL for calculation of flow velocities about a Hess-Smith three-dimensional body. SETFLO reads a four-character Hollerith identification of the body and checks to see if it is identical to the identification obtained from unit 14. If not, a comment is printed and the calculation is stopped.

If flow around the body is calculated by some means other than the Hess-Smith method, SETFLO must be replaced with a dummy subroutine.

Subroutine DVDQ

This is the variable order, ordinary differential equation integrator of Krogh (ref. 11). Operating instructions, which have proven to be quite adequate, are found in the glossary of the DVDQ card listings. The version used here automatically adapts to the word size of the computer used.

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*Be very sure that IMPACT does not adjust initial trajectory coordinates during tangent trajectory determination under control of TANTRA.

PROGRAM ARYTRJ

General Description

SR TRAJECT is called to compute particle trajectories initiated at an array of points in three-dimensional space. Particle properties are computed by SR PARTCL and SR PRFUN. Flow velocities are computed by SR FLOVEL, which uses data that, for example, are prepared by program BOXC for flow around an arbitrary three-dimensional body. SR DVDQ integrates the particle equations of motion.

Initial coordinates of the initial point array, array increment values for the three coordinate directions and the number of increments desired along each direction (including the initial point) are input. Also input are integers M(3) which control the order of incrementing along the three axes and a skip parameter NSKIP. For example, suppose M(1) = 3, M(2) = 1, M(3) = 2:

1. The x and z coordinates are held fixed while y is incremented over its range.

2. y is returned to its initial value, z is incremented once, and y is incremented over its range.

3. This is repeated until z covers its complete range.

4. z is returned to its initial value, x is incremented once, and y is incremented over its complete range.

5. etc.

Trajectories are computed to the limiting x coordinate value XLIMIT or until penetration of the body is sensed.

If not every trajectory is desired, the parameter NSKIP is set greater than zero. Then, after the first trajectory, only every NSKIP + 1 th trajectory is computed.

Subroutines Required

FLOVEL, SETFLO, PARTCL, FALWAT, TRAJECT, IMPACT (dummy), PRFUN, DVDQ, WCDRR, CDRR

External Storage Units

Units 5 and 6 are the system input and print units, respectively.
Unit 9 is used for temporary storage.
Unit 10 is used to store trajectory data for plotting by PGM STEREO.
Unit 14 is used by SR SETFLO for input of data prepared by PGM BOXC.

Printed Output

The printed output is largely self-explanatory. For each trajectory are printed at time interval TPRINT: time, point coordinates (X, Y, Z), particle velocity components (VPX, VPY, VPZ), flow velocity components (VX, VY, VZ), time step (H), Reynolds number (R), acceleration modulus (AC) and cumulative number of flow velocity computations (NEVAL). (All dimensionless)

Other quantities are: angle between the projection of the initial flow velocity vector in the z = 0 plane and the x axis (ALPHAO), angle between the initial flow velocity vector and its projection in the z = 0 plane (BETAO), angle between the projection of the final particle velocity vector in the z = 0 plane and the x axis (ALPHAR), angle between the final particle velocity vector and its projection in the z = 0 plane (BETAR), direction cosines of the drag vector at the final point, and the angle between the projection of the drag vector in the z = 0 plane and the x axis (A), and the angle between the drag vector and the z axis (GAMMA). (All angles are in degrees.)

ARYTRJ Card Input

Card No.	Variables and Format	Description	
1	KASE, (A4)	Body identification. Read by SR SETFLO. Must be identical to parameter KASE on card 1 of the BOXC input.	
2	HOLL (18), IPLOT, (18A4, 7X, L1)	HOLL	72 columns of Hollerith run identification
		IPLOT (col. 80)	Logical variable: if true, trajectory data are written on unit 10 for plotting by PGM STEREO.
3	V, ELL, RHO, TEMP, XFINAL, (8F10.5)	V	Free stream airspeed (m s^{-1})
		ELL	Characteristic dimension of the body (m). Corresponds to L as defined for eq. (1).
		RHO	Ambient air density (kg m^{-3})
		TEMP	Ambient temperature ($^{\circ}K$)
		XFINAL	x coordinate for trajectory cut off (i.e., maximum x coordinate) (normalized, dimensionless)
4	TPRINT, HI, HMINI, EPSI(3), (8F10.5)	TRRINT	Time interval for trajectory point print. Default value = 0.1.
		HI	Initial numerical integration time step. (See SR DVDQ). Default value = 0.1
		HMINI	Initial numerical integration minimum time step. (See SR DVDQ). Default value = .005.
		EPSI(3)	Parameters used to control numerical integration local error. (See SR DVDQ). Default values = 1.0E-5.
		All normalized, dimensionless.	
5	DIAM, (7F10.0)	Water drop diameter (μm). This card is read by SR PARTCL.	
6	M(3), NSKIP, (4I4)	M(3)	Array incrementation control
		NSKIP	Array skip parameter (See discussion above.)
7	X(I), D(I), N(I); I = 1 (2F10.0, I4)	X(1)	Initial x coordinate (dimensionless)
		D(1)	x coordinate increment (dimensionless)
		N(1)	Number of increments desired in the x direction (including the initial value)
8	X(I), D(I), N(I); I = 2	Same as card 7, but for the y direction.	
9	X(I), D(I), N(I); I = 3	Same as card 7, but for the z direction.	
5'	Cards 5 - 9 are repeated for another particle and another array		
.	.		
.	.		
.	.		
5	Blank card	A blank card 5 terminates the run.	

PROGRAM CONFAC

General Discussion

Program CONFAC computes trajectories to user-specified target points. It operates in two modes:

1. Single trajectories are calculated to each target point (NW = 0).

2. A central trajectory is computed to the target point, and NW trajectories, evenly spaced about a circle in the target plane of radius RW about the central trajectory, are calculated such as to define a particle flux tube.

Mode 2 is used to calculate concentration factor, C_F, which is the ratio of particle flux at the target point to the free-stream particle flux. It is easy to show that

$$C_F = \frac{\text{area of flux tube cross section in the free stream}}{\text{area of flux tube cross section at the target point}}$$

The areas are those of plane polygons of NW vertices as calculated by SR POLYGON. Concentration ratio, C_M, the ratio of particle concentration at the target point to free stream concentration, is obtained via the relation

$$C_M = C_F/|\vec{v}_p| \quad .$$

The desired trajectories are calculated by an iterative method which finds a trajectory that passes within a user-specified distance tolerance (RW*TOL) of the desired target point. To initialize, the user may input four sets of coordinate guesses: two sets of y and z coordinates for the initial and target planes. No special care need be taken in making these guesses since convergence should be rapid as long as the coordinates are in the correct general neighborhood. On default of input, the initial coordinate guesses are supplied by the code.

The trajectory iteration procedure is described in detail in reference 1. (See pp. 13 - 16 and Appendix A.) SR MAP controls the iteration and calls SR TRAJECT to calculate trajectories. If convergence is not achieved after calculating twenty-five trajectories, the calculation proceeds to the next particle or stops. The limiting number of trajectories can be changed by changing the value of ILIM in a DATA statement in SR MAP.

SR IMPACT is a problem-specific code whose purpose is to adjust trajectory initial y and z coordinates when penetration of the body occurs such that penetration will be avoided on the next attempt. After twenty-five penetrations, the calculation proceeds to the next particle or stops. The limiting number of penetrations can be changed by changing the value of JLIM in PGM CONFAC.

Subroutines Required

FLOVEL, MAP, PARTCL, POLYGON, DVDQ, SETFLO, FALWAT, PRFUN, IMPACT, TRAJECT, TRANSFM, MATINV, WCDRR, CDRR.

External Storage Units

Same as for ARYTRJ.

Printed Output

The printed output is largely self-explanatory, and contains all of the data described for PGM ARYTRJ.

Detailed trajectory data are printed only for the final trajectory which is the result of a successful convergence to the desired target point. For

other trajectories, only the initial and final y and z coordinates are printed. Except for the initial coordinate guesses, these coordinates are given in the "flux tube coordinate system", and are so identified and distinguished in the output from the "flow coordinate system". The "flow system" is the coordinate system (normalized) by use of which the body is described and the flow is computed. The "flux tube system" at any point along the trajectory has its origin at the flux tube center and its y and z axis in the plane normal to the central trajectory. Flux tube system coordinates are given in the initial and target planes in the output.

For cases where flux tubes are calculated, a summary of the initial and final coordinates of all NW + 1 trajectories are printed, the areas of the polygons with NW vertices in the initial and final planes are printed, and the concentration factor and concentration ratio are printed.

CONFAC Card Input

Card No.	Variables and Format	Description	
1	KASE, (A4)	Body identification. Read by SR SETFLO. Must be identical to parameter KASE on card 1 of the BOKC input.	
2	HOLL(18), IPLOT, (18A4, 7X, L1)	HOLL	72 columns of Hollerith run identification.
		IPLOT (col. 80)	Logical variable: if true, trajectory data are written on unit 10 for plotting by PGM STEREO.
3	V, ELL, RHO, TEMP, XSTART, (8F10.5)	V	Free stream airspeed (m s^{-1})
		ELL	Characteristic dimension of the body (m). Corresponds to L as defined for eq. (1).
		RHO	Ambient air density (kg m^{-3}).
		TEMP	Ambient temperature (^{0}K).
		XSTART	Initial x coordinate of trajectory. (normalized, dimensionless)
4	TPRINT, HI, HMINI, EPSI(3), (8F10.5)	Same as for ARYTRJ.	
5	NW, RW, TOL, (I10, 7F10.5)	NW	Number of trajectories used to define flux tube peripheries for concentration factor calculation. If NW = 0, single trajectories are calculated to target points defined by cards 9.
6	YE(I), ZE(I), YI(I), Z(I); (I = 2), (8F10.5)	YE, ZE	Initial guesses of trajectory y and z coordinates in the target plane.
7	YE(I), ZE(I), YI(I), Z(I); (I = 3), (8F10.5)	YI, ZI	Initial guesses of trajectory coordinates in the initial plane.
		These coordinates are in the coordinate system used to define the body and the flow field (normalized, dimensionless). The data in the two cards can be very approximate, but if not blank, the two cards should not be identical. On input of two blank cards, the code supplies default estimates based on the first target coordinates.	
8	DIAM, (7F10.0)	Water drop diameter (μm). This card is input by SR PARTCL.	
9	XW, YW, ZW, (8F10.5)	x,y,z coordinates of the target point (normalized, dimensionless).	
8'	Cards 8 and 9 are repeated for as many particles as desired.*		
9'			
.	.		
.	.		
.	.		
.	.		
8	Blank card	A blank card 8 terminates the run.	

*Previous trajectory y and z coordinates are used as trajectory iteration initialization estimates for each new target point. Thus, if target points are widely spaced, separate runs should be made for each.

PROGRAM TANTRA

General Discussion

The purpose of this code is to compute tangent particle trajectories to a three-dimensional body. The code is designed to be as general and as automatic as practical, but owing to the unlimited number of geometrical possibilities in three dimensions, some compromise is necessary. Since we cannot know a priori what parts of a body the tangents will touch, we do not, in general, have the option of specifying target points on the body or even target planes through the body. Therefore, we specify curves in the free stream well ahead of the body on which all trajectories are initiated for a particular tangent determination.

Given the equation of the starting-point curve and an initial point on the curve, the code computes the trajectory from this point toward the body until penetration of the body occurs or until a specified x-coordinate stop point is reached. If penetration occurs, a specified coarse step is taken along the starting-point curve in direction away from the body, and another trajectory is computed. If penetration does not occur, the coarse step is taken along the starting-point curve in direction toward the body, and another trajectory is calculated. Once penetration occurs for trajectories that initially miss the body, or the reverse for trajectories that initially impact, the initial point is backed up one step along the curve away from the body if necessary, and the process of stepping toward the body is resumed with a fine step size until the tangent trajectory is found. Thus, the tangent trajectory misses the body by no greater than the tolerance implied by the fine step size. Note that this does not imply that the tolerance is the fine step size. Separation of trajectories in the free stream will not be the same as separation of the same trajectories near the body, nor even approximately the same except for very large, heavy particles which have sufficient inertia to essentially ignore the flow around the body. In general, trajectory separations near the body will be less than in the free stream.

Specification of the starting-point curve is done via SR STRPNT, which in the version supplied uses straight line curves. The user provides the coordinates of two points on the line:

Point 1. Initial coordinates of the initial trajectory

Point 2. Coordinates of any other point on the line which is closer to the body than Point 1.

Point 2 must be closer to the body than Point 1 to ensure that stepping along the starting-point curve proceeds in the proper direction. Point 2 need not be, and in general will not be, the initial point of a trajectory. Note that both of these points must be sufficiently far upstream to be essentially in the free stream. Also specified are the coarse and fine stepping distances. All coordinates and distances are normalized. (See eq. (1).)

If so specified (IPLOT = true), tangent trajectory data are stored on unit 10 for plotting later by PGM STEREO.

Subroutines Required

FLOVEL, SETFLO, PARTCL, FALWAT, STRPNT, TRAJECT, IMPACT*, PRFUN, DVDQ, WCDRR, CDRR.

External Storage Units

Same as for ARYTRJ.

Printed Output

Trajectory data are as described for PGM ARYTRJ and are printed for every trajectory computed regardless of whether or not the trajectory is

*Be sure that IMPACT is a dummy subroutine. Resetting of initial trajectory coordinates by SR IMPACT will ruin a tangent trajectory determination.

accepted as the tangent trajectory. Beyond that, the output is fully labeled and self-explanatory. All input data are printed: including the points used to define the starting-point line, coarse and fine increments, and starting point coordinates. The switching from coarse to fine step size is clearly identified, as are the tangent trajectory data.

TANTRA Card Input

Card No.	Variables and Format	Data Description
1-4		Cards 1 through 4 are the same as for ARYTRJ.
5	DIAM, (7F10.0)	Water drop diameter (μm). This card is read by SR PARTCL.
6	DCORS, DFINE, (8F10.0)	Respectively, the coarse and fine step sizes to be used in stepping along the starting-point line (normalized, dimensionless). Card 6 is read by SR STRPNT.
7	X,Y,Z,X1,Y1,Z1, (8F10.0)	X,Y,Z — Coordinates of Point 1, which specifies the initial trajectory coordinates on the starting-point line (normalized, dimensionless). X1,Y1,Z1 — Coordinates of Point 2, which is any point on the starting-point line that is closer to the body than Point 1 (normalized, dimensionless). Note that the starting-point line should be far enough upstream of the body to be essentially in the free stream. Card 7 is read by SR STRPNT.
6' 7'		Cards 6 and 7 are repeated for as many trajectories as desired.
6	Blank card	A blank card 6 signals end of calculation for this water drop, and another card 5 is read.
5' 6" 7" . . .		
6	Blank card	
5	Blank card	A blank card 5 terminates the run.

PROGRAM STEREO

General Discussion

Program STEREO is used to plot results of the trajectory calculations. Both body and trajectories are plotted. The body data are obtained from unit 9, on which the data were stored by SR PINPUT under control of PGM PBOXC, and the trajectory data are obtained from unit 10, on which the data were stored under control of either ARYTRJ, CONFAC or TANTRA.

Plots are prepared in pairs, members of a pair being separated by a specified angle on each side of a specified viewing direction. Proper specification of the angles, which usually requires some trial-and-error-experimentation, may provide plots which can be used for stereo viewing as illustrated by Figure 6.

The viewing direction is defined by specifying two angles, THETA and PSI. The operation of these angles is as follows: We assume a right-handed coordinate system with its positive z axis directed upward and the free-stream flow in the direction of the positive x axis. First rotate the coordinate system about the y axis by angle THETA such that positive THETA tilts the positive x axis upward. Then rotate about the new z axis by angle PSI such that for positive PSI the rotation is clockwise when viewed from above. The view direction separation angle, DELTA is applied to angle PSI such that the members of a stereo pair are actually viewed from angles THETA, PSI-DELTA and THETA, PSI + DELTA, and are plotted in that order.

For a particular case (i.e., body and set of trajectories), the user must specify the number of trajectories and the (upstream) x coordinate at which plotting of the trajectory data is to be begun. This need not have the same value as the initial x coordinates of the data stored on unit 10.

Translating and scaling of the data such that it will properly fit into the plot area is handled automatically by the program.

Only system and plot subroutines are required.

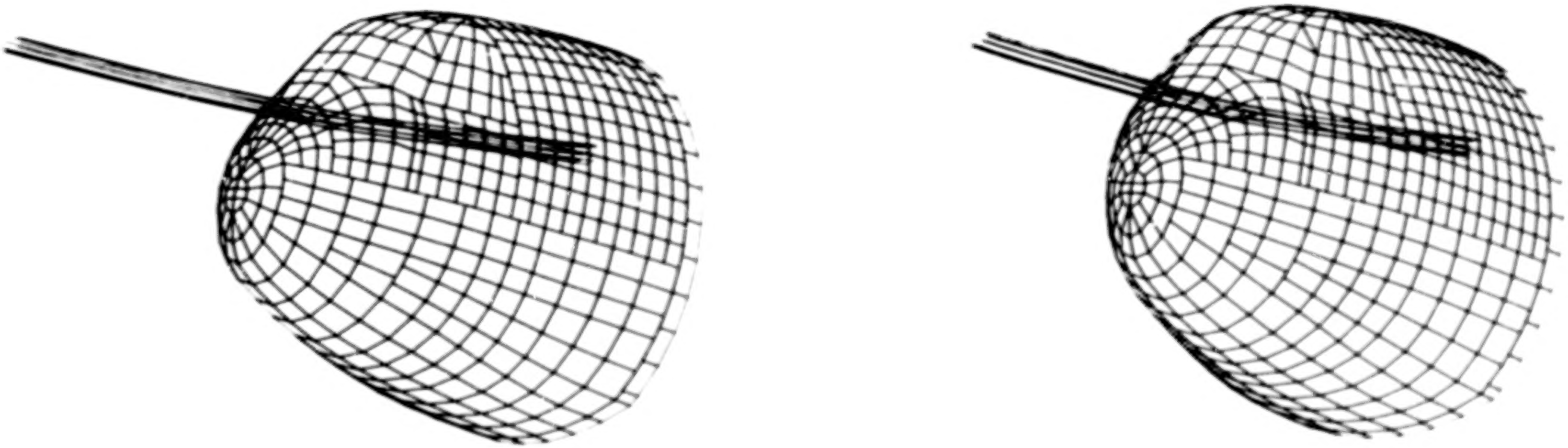

Figure 6. Stereographic plots of an eight-trajectory, 20 μm-diameter water drop flux tube to a particle replicator mounted on the forward fuselage of a Lockheed C130A airplane. The central trajectory is also shown. C_F = 1.15. (Ref. 1) Three-dimensional perspective can be attained by staring at the center of the figure and then crossing the eyes such that the two images merge.

External Storage Units

Units 5 and 6 are the system input and print units.

Unit 9 contains the three-dimensional body surface data, plus some scaling information, as stored by SR PINPUT.

Unit 10 contains the trajectory data as stored under control of PGMS ARYTRJ, CONFAC or TANTRA.

Printed Output

The printed output is simple. It consists of a run identification, the input data and some scaling information. For each trajectory is printed: 1. the coordinates (XTRAJ, YTRAJ, ZTRAJ) of each point before translation, scaling and projection onto the plot plane, and 2. the translated, scaled and projected coordinates (XPLOT, YPLOT) of each point plotted.

STEREO Card Input

Card No.	Variables and Format	Description	
1	HOLL(18), (18A4)	72 columns of Hollerith run identification.	
2	ICRT, NTRJS, XSTART, (L1, I9, F10.0)	ICRT	A logical variable which when true causes plotting to be via CRT. Otherwise, plotting is via pen and ink.
		NTRJS	Number of trajectories to be plotted.
		XSTART	x coordinate at which trajectory plotting is to begin. Need not correspond to the initial x coordinates of trajectories stored on unit 10.
3,4	LINE1, LINE2, (7A6/7A6)	Cards 3 and 4 are read only if ICRT is true (card 2). Two lines of 42 columns each of Hollerith labeling for a microfiche film.	
5,6	THETA, PSI, DELTA, HLABEL(18), (3F10.2/ 18A4)	THETA PSI DELTA	Viewing angles and viewing angle separation (degrees). (See definitions above.)
		HLABEL	72 columns of Hollerith labeling for the plots.

- -

5',6' Cards 5 and 6 are repeated for as many additional plot pairs as desired.

- -

5,6	Blank cards	Blank cards 5 and 6 terminate the run.	

VALIDATION

PRIOR WORK

Hess and Smith (refs. 9 and 10) present results of a wide range of studies where flow velocities and pressures calculated by their method are compared with other theory and with experiment. Outstanding agreement with the data from other sources is evident.

In reference 1 we present results of several studies that examine accuracy of the trajectory calculations. To check accuracy of the numerical integrations we computed trajectories of 1 μm diameter water drops in axisymmetric airflow about an ellipsoid of fineness ratio 2 and found the largest deviation from the stream line flow to be 0.006%. Thus very small particles are computed to essentially follow the stream flow as they should do.

To determine differences between trajectories computed by a body constructed from Hess-Smith panels and a body with an analytically defined surface, we computed trajectories of water drops about ellipsoids of fineness ratio 2 of both types in axisymmetic air flow at 5 kft altitude in a standard atmosphere (ref. 1). The Hess-Smith ellipsoid was constructed from 1800 panels, and the length of the semi-major axes of the ellipsoids was taken to be 4.67m. Results are shown in Fig. 7 for comparison of trajectory intersections with the extended minor axis. All of the Hess-Smith points are slightly farther from the ellipsoid surface than the analytical points, but the discrepancies are not large. The largest discrepancy, for 100 μm drops at 31 cm, is very atypical in that this point is on the edge of a shadow zone, where: trajectory distortions are near their maxima, concentration factors become very large, and we expect and find "pathlogical" computational results caused by trajectories crossing each other in this region of extremely high concentration gradients.

Also in reference 1 we compare our tangent trajectories with those calculated by Dorsch et al. (ref. 19) for axisymmetric flow about an ellipsoid

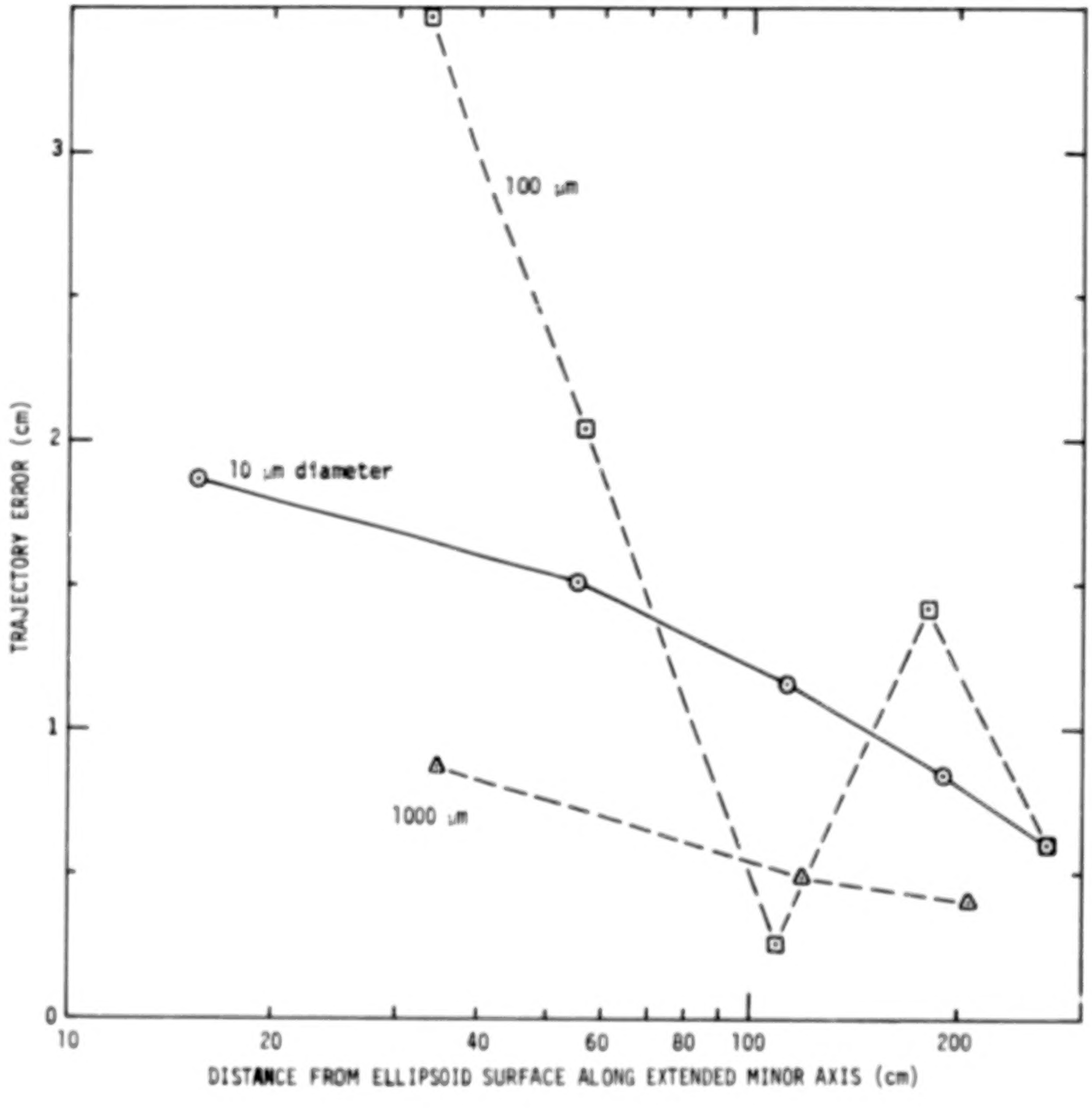

Figure 7. Comparison of water drop trajectories about an ellipsoid of fineness ratio 2 using exact and approximate potential airflow. The ellipsoid semi-minor axis is of length 2.335m. (From ref. 1)

of fineness ratio 5 for the two conditions of flow and particle size given in Figure 4 of reference 19. Particle equations of motion without gravity were used. In terms of the distance of the tangent trajectory from the symmetry axis in the free stream, r_o, we have

		r_o	
Stokes Number	Free Stream Reynolds Number	Dorsch, et al., ref. 19	Norment and Zalosh, ref. 1
1	4096	.077	.075
1/30	512	.020	.015

Here r_o is a fraction of the ellipsoid semi-major axis length. Differences in our method of calculation and that of Dorsch et al. are discussed in the next section.

ADDITIONAL VERIFICATION

The work of comparison of calculated tangent trajectories to an ellipsoid of fineness ratio 5 with those calculated by Dorsch et al. (ref. 19) was extended to include cases given in Table 1 of reference 19. Three cases were chosen for study as follows:

Altitude: 5000 ft Temperature: 20°F

Water droplet diameter: 20 μm

Ellipsoid semi-major axis length: 5 ft.

Free stream speeds: 100, 300, 500 mph.

The Dorsch, et al. calculations were done neglecting gravity, with use of very early drag data and the equations of motion were integrated with a mechanical differential analyser. Our calculations included gravity and were done by the codes described herein. In both studies flow about an analytical ellipsoid was used. Our calculations were three-dimensional, but confined to the y = 0 plane. To account for effects of gravity (i.e., droplet settling) we calculated

tangent trajectories above and below the ellipsoid and averaged the results. (If r_0 values are adjusted for droplet settling between initial and impact points, the result is the same as the average r_0 values obtained from the above and below tangent trajectories.) Results are:

Free Stream Speed (mph)	r_0			
	Dorsch, et al., Ref. 19	This Study		
		Upper Side	Lower Side	Average
100	.024	.0198	.0174	.019
300	.041	.0373	.0365	.037
500	.054	.0460	.0456	.045

Lewis and Ruggeri (ref. 20) present experimental data obtained in the NACA Lewis wind tunnel used for icing studies. Data were obtained at constant free stream airspeed and atmospheric conditions for axisymmetric flow about an ellipsoid of fineness ratio 2.5. Local impingment efficiencies were measured as a function of s/R (s is the distance measured aftward along the ellipsoid surface from the nose of the ellipsoid, and R is the semi-minor ellipsoid axis) for four narrow distributions of droplet sizes. The relevant datum here is the maximum s/R for each droplet distribution which is produced by the maximum droplet diameter, δ_{max}, in its distribution.

Lewis and Ruggeri give the following flow and dimensional data:

Free stream speed: 157 kts (80.767 m s^{-1})

Temperature: 50°F (283.16°K)

Pressure: 28" Hg (94583 Pa)

Semi-minor ellipsoid axis: 15 inches (0.381m)

We calculate air density to be 1.1637 kg m^{-3}.

Lewis and Ruggeri also give theoretical s/R results. Our calculations were done as described previously in this section. x,z coordinates of limiting impingement points were converted to $(s/R)_{max}$ values by a graphical method. Results are as follows:

δ_{max} (μm)	$(s/R)_{max}$ From Ref. 20: Exp. Mean from Figs. 10,23	$(s/R)_{max}$ From Ref. 20: Theor. from Fig. 23	% Error Relative to Exp.	$(s/R)_{max}$ This Study	% Error Relative to Exp.	% Error Relative to Ref. 20 Theory
24	.23	.52	+160	.385	+67	-26
35	.405	.75	+ 88	.648	+60	-14
45	.525	.9	+ 64	.847	+61	- 6
64.5	.745	1.2	+ 60	1.18	+58	-1.7

Note that in all cases our calculations are closer to the experimental values, though for the larger particles our theoretical results differ little from those reported by Lewis and Ruggeri.

EXAMPLE PROBLEMS

GENERAL DISCUSSION

Example card input data are given below and printouts are presented in the microfiche addition included with this report for each of the seven codes listed in Table 1. A special three-dimensional test body, which is described in the next section, was used for the calculations.

All of the codes use less than 65,000 central processor storage words, and most use substantially less. Program BOXC uses the most storage and STEREO uses the least.

Total running times on the UNIVAC 1100/42 computer at NASA Lewis Research center for the example problems are:

Code	Total Running Time (minutes : seconds)
PBOXC	0:54
BOXC	4:23
FLOPNT	0:39
ARYTRJ	1:24
CONFAC	2:44
TANTRA	2:47
STEREO	0:47

THE TEST BODY

A special asymmetric test body was designed and is described in terms of 189 Hess-Smith panels. A listing of the data cards for the body follows the PBOXC card input below, and Fig. 8 shows computer plots of the body.

The structure of the body is as follows:

1. The more pointed end, which faces the free stream flow, is half of a prolate ellipsoid

$$\frac{x^2}{9} + \frac{y^2}{4} + z^2 = 1; \; -3 \leq x \leq 0.$$

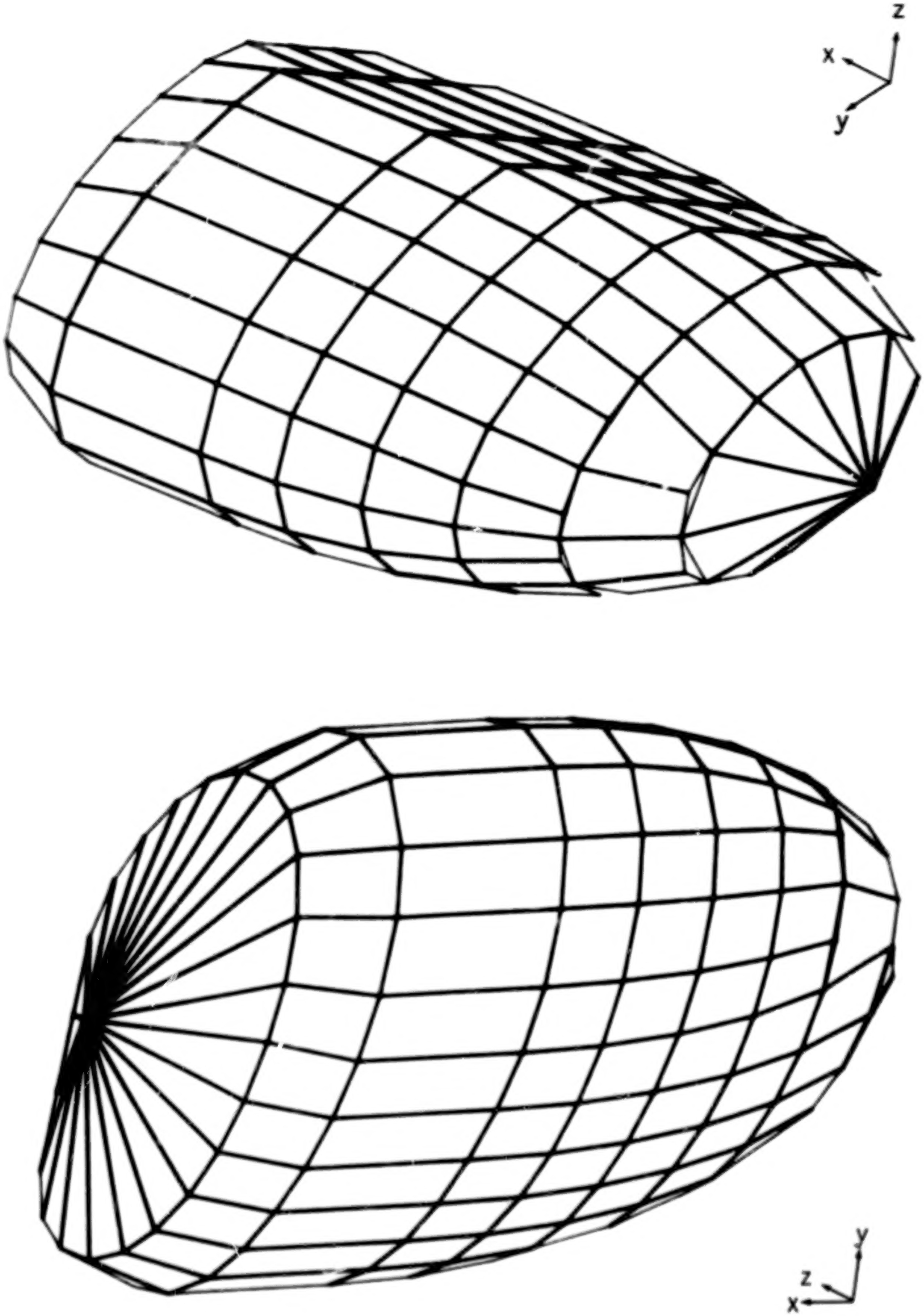

Figure 8. Asymmetric test problem body.

2. The central section is a cylinder

$$\frac{y^2}{4} + z^2 = 1 \; ; \quad 0 \leq x \leq 1.$$

3. The blunt end is half of an oblate ellipsoid

$$(x - 1)^2 + \frac{y^2}{4} + z^2 = 1 \; ; \quad 1 \leq x \leq 2.$$

4. The body is truncated by the plane

$$y - 2z = 2.$$

EXAMPLE PROBLEM/CARD INPUT AND PRINTOUT

PBOXC

Card No.*	Card contents (columns 1–80)
1	TEST BODY . . . TEST
3	FFTTT
5A	2.0 . . . 2 1 . . . 1 . . . SMBD 1
	2.0 . . . 1 . . . 2 . . . SMBD 2
	2.0 . . . 1 . . . 3 . . . SMBD 3
	(See data card listing which follows.)
6	TEST BODY PLOTS
7	02/14/80

*Card numbers are the same as those given in the code description section.

Numbers punched in columns 35-36 and 45-46 correspond to the m and n designations used to organize the data. They are not read by the computer. (See pp. 16 ff.)

Test Problem Data Cards

Columns: 10 ↓ 20 ↓ 30 ↓ 32 ↓

2.0			2	1	1	SMBD	1
2.0				1	2	SMBD	2
2.0				1	3	SMBD	3
2.0				1	4	SMBD	4
2.0				1	5	SMBD	5
2.0				1	6	SMBD	6
2.0				1	7	SMBD	7
2.0				1	8	SMBD	8
2.0				1	9	SMBD	9
2.0				1	10	SMBD	10
2.0				1	11	SMBD	11
2.0				1	12	SMBD	12
2.0				1	13	SMBD	13
2.0				1	14	SMBD	14
2.0				1	15	SMBD	15
2.0				1	16	SMBD	16
2.0				1	17	SMBD	17
2.0				1	18	SMBD	18
2.0				1	19	SMBD	19
2.0				1	20	SMBD	20
2.0				1	21	SMBD	21
2.0				1	22	SMBD	22
2.0				1	23	SMBD	23
2.0				1	24	SMBD	24
1.5	1.7320	0.0	1	2	1	SMBD	25
1.5	1.67	0.2297		2	2	SMBD	26
1.5	1.46	0.4659		2	3	SMBD	27
1.5	1.14	0.6520		2	4	SMBD	28
1.5	0.8	0.7681		2	5	SMBD	29
1.5	0.4	0.8426		2	6	SMBD	30
1.5	0.0	0.8660		2	7	SMBD	31
1.5	-0.4	0.8		2	8	SMBD	32
1.5	-0.8	0.6		2	9	SMBD	33
1.5	-1.2	0.4		2	10	SMBD	34
1.5	-1.6	0.2		2	11	SMBD	35
1.5	-1.7320	0.0		2	12	SMBD	36
1.5	-1.67	-0.2297		2	13	SMBD	37
1.5	-1.46	-0.4659		2	14	SMBD	38
1.5	-1.14	-0.6520		2	15	SMBD	39
1.5	-0.8	-0.7681		2	16	SMBD	40
1.5	-0.4	-0.8426		2	17	SMBD	41
1.5	0.0	-0.8660		2	18	SMBD	42
1.5	0.4	-0.8426		2	19	SMBD	43
1.5	0.8	-0.7681		2	20	SMBD	44
1.5	1.14	-0.6520		2	21	SMBD	45
1.5	1.46	-0.4659		2	22	SMBD	46
1.5	1.67	-0.2297		2	23	SMBD	47
1.5	1.7320	0.0		2	24	SMBD	48
1.0	2.0	0.0	1	3	1	SMBD	49
1.0	1.87	0.3546		3	2	SMBD	50
1.0	1.6	0.6		3	3	SMBD	51
1.0	1.2	0.8		3	4	SMBD	52
1.0	0.8	0.9165		3	5	SMBD	53
1.0	0.4	0.9798		3	6	SMBD	54
1.0	0.0	1.0		3	7	SMBD	55
1.0	-0.4	0.8		3	8	SMBD	56

1.0	-0.8	0.6		3	9	SMBD 57
1.0	-1.2	0.4		3	10	SMBD 58
1.0	-1.6	0.2		3	11	SMBD 59
1.0	-2.0	0.0		3	12	SMBD 60
1.0	-1.87	-0.3546		3	13	SMBD 61
1.0	-1.6	-0.6		3	14	SMBD 62
1.0	-1.2	-0.8		3	15	SMBD 63
1.0	-0.8	-0.9165		3	1	SMBD 64
1.0	-0.4	-0.9798		3	1	SMBD 65
1.0	0.0	-1.0		3	18	SMBD 66
1.0	0.4	-0.9798		3	19	SMBD 67
1.0	0.8	-0.9165		3	20	SMBD 68
1.0	1.2	-0.8		3	21	SMBD 69
1.0	1.6	-0.6		3	22	SMBD 70
1.0	1.87	-0.3546		3	23	SMBD 71
1.0	2.0	0.0		3	24	SMBD 72
0.0	2.0	0.0	1	8	1	SMBD 73
0.0	1.87	0.3546		8	2	SMBD 74
0.0	1.6	0.6		8	3	SMBD 75
0.0	1.2	0.8		8	4	SMBD 76
0.0	0.8	0.9165		8	5	SMBD 77
0.0	0.4	0.9798		8	6	SMBD 78
0.0	0.0	1.0		8	7	SMBD 79
0.0	-0.4	0.8		8	8	SMBD 80
0.0	-0.8	0.6		8	9	SMBD 81
0.0	-1.2	0.4		8	10	SMBD 82
0.0	-1.6	0.2		8	11	SMBD 83
0.0	-2.0	0.0		8	12	SMBD 84
0.0	-1.87	-0.3546		8	13	SMBD 85
0.0	-1.6	-0.6		8	14	SMBD 86
0.0	-1.2	-0.8		8	15	SMBD 87
0.0	-0.8	-0.9165		8	16	SMBD 88
0.0	-0.4	-0.9798		8	17	SMBD 89
0.0	0.0	-1.0		8	18	SMBD 90
0.0	0.4	-0.9798		8	19	SMBD 91
0.0	0.8	-0.9165		8	20	SMBD 92
0.0	1.2	-0.8		8	21	SMBD 93
0.0	1.6	-0.6		8	22	SMBD 94
0.0	1.87	-0.3546		8	23	SMBD 95
0.0	2.0	0.0		8	24	SMBD 96
-0.5	1.9720	0.0	1	9	1	SMBD 97
-0.5	1.85	0.3415		9	2	SMBD 98
-0.5	1.585	0.5866		9	3	SMBD 99
-0.5	1.195	0.7844		9	4	SMBD 100
-0.5	0.8	0.9012		9	5	SMBD 101
-0.5	0.4	0.9655		9	6	SMBD 102
-0.5	0.0	0.9860		9	7	SMBD 103
-0.5	-0.4	0.8		9	8	SMBD 104
-0.5	-0.8	0.6		9	9	SMBD 105
-0.5	-1.2	0.4		9	10	SMBD 106
-0.5	-1.6	0.2		9	11	SMBD 107
-0.5	-1.9720	0.0		9	12	SMBD 108
-0.5	-1.85	-0.3415		9	13	SMBD 109
-0.5	-1.585	-0.5866		9	14	SMBD 110
-0.5	-1.195	-0.7844		9	15	SMBD 111
-0.5	-0.8	-0.9012		9	16	SMBD 112

-0.5	-0.4	-0.9655		9	17	SMBD 113
-0.5	0.0	-0.9860		9	18	SMBD 114
-0.5	0.4	-0.9655		9	19	SMBD 115
-0.5	0.8	-0.9012		9	20	SMBD 116
-0.5	1.195	-0.7844		9	21	SMBD 117
-0.5	1.585	-0.5866		9	22	SMBD 118
-0.5	1.85	-0.3415		9	23	SMBD 119
-0.5	1.9720	0.0		9	24	SMBD 120
-1.0	1.9856	0.0	1	10	1	SMBD 121
-1.0	1.785	0.3039		10	2	SMBD 122
-1.0	1.54	0.5440		10	3	SMBD 123
-1.0	1.175	0.7374		10	4	SMBD 124
-1.0	0.8	0.8538		10	5	SMBD 125
-1.0	0.4	0.9214		10	6	SMBD 126
-1.0	0.0	0.9428		10	7	SMBD 127
-1.0	-0.4	0.8		10	8	SMBD 128
-1.0	-0.8	0.6		10	9	SMBD 129
-1.0	-1.2	0.4		10	10	SMBD 130
-1.0	-1.6	0.2		10	11	SMBD 131
-1.0	-1.9856	0.0		10	12	SMBD 132
-1.0	-1.785	-0.3039		10	13	SMBD 133
-1.0	-1.54	-0.5440		10	14	SMBD 134
-1.0	-1.175	-0.7374		10	15	SMBD 135
-1.0	-0.8	-0.8538		10	16	SMBD 136
-1.0	-0.4	-0.9214		10	17	SMBD 137
-1.0	0.0	-0.9428		10	18	SMBD 138
-1.0	0.4	-0.9214		10	19	SMBD 139
-1.0	0.8	-0.8538		10	20	SMBD 140
-1.0	1.175	-0.7374		10	21	SMBD 141
-1.0	1.54	-0.5440		10	22	SMBD 142
-1.0	1.785	-0.3039		10	23	SMBD 143
-1.0	1.9856	0.0		10	24	SMBD 144
-1.5	1.7320	0.0	1	11	1	SMBD 145
-1.5	1.67	0.2297		11	2	SMBD 146
-1.5	1.46	0.4659		11	3	SMBD 147
-1.5	1.14	0.6520		11	4	SMBD 148
-1.5	0.8	0.7681		11	5	SMBD 149
-1.5	0.4	0.8426		11	6	SMBD 150
-1.5	0.0	0.8660		11	7	SMBD 151
-1.5	-0.4	0.8		11	8	SMBD 152
-1.5	-0.8	0.6		11	9	SMBD 153
-1.5	-1.2	0.4		11	10	SMBD 154
-1.5	-1.6	0.2		11	11	SMBD 155
-1.5	-1.7320	0.0		11	12	SMBD 156
-1.5	-1.67	-0.2297		11	13	SMBD 157
-1.5	-1.46	-0.4659		11	14	SMBD 158
-1.5	-1.14	-0.6520		11	15	SMBD 159
-1.5	-0.8	-0.7681		11	16	SMBD 160
-1.5	-0.4	-0.8426		11	17	SMBD 161
-1.5	0.0	-0.8660		11	18	SMBD 162
-1.5	0.4	-0.8426		11	19	SMBD 163
-1.5	0.8	-0.7681		11	20	SMBD 164
-1.5	1.14	-0.6520		11	21	SMBD 165
-1.5	1.46	-0.4659		11	22	SMBD 166
-1.5	1.67	-0.2297		11	23	SMBD 167
-1.5	1.7320	0.0		11	24	SMBD 168

-2.0	1.4907	0.0	1	12	1	SMBD 169
-2.0	1.465	0.1378		12	2	SMBD 170
-2.0	1.322	0.3444		12	3	SMBD 171
-2.0	1.072	0.5179		12	4	SMBD 172
-2.0	0.8	0.6289		12	5	SMBD 173
-2.0	0.4	0.7180		12	6	SMBD 174
-2.0	0.0	0.7454		12	7	SMBD 175
-2.0	-0.4	0.7180		12	8	SMBD 176
-2.0	-0.8	0.6		12	9	SMBD 177
-2.0	-1.2	0.4		12	10	SMBD 178
-2.0	-1.4	0.2560		12	11	SMBD 179
-2.0	-1.4907	0.0		12	12	SMBD 180
-2.0	-1.465	-0.1378		12	13	SMBD 181
-2.0	-1.322	-0.3444		12	14	SMBD 182
-2.0	-1.072	-0.5179		12	15	SMBD 183
-2.0	-0.8	-0.6289		12	16	SMBD 184
-2.0	-0.4	-0.7180		12	17	SMBD 185
-2.0	0.0	-0.7454		12	18	SMBD 186
-2.0	0.4	-0.7180		12	19	SMBD 187
-2.0	0.8	-0.6289		12	20	SMBD 188
-2.0	1.072	-0.5179		12	21	SMBD 189
-2.0	1.322	-0.3444		12	22	SMBD 190
-2.0	1.465	-0.1378		12	23	SMBD 191
-2.0	1.4907	0.0		12	24	SMBD 192
-2.0	1.4907	0.0	2	13	1	SMBD 193
-2.0	1.322	0.3444		13	2	SMBD 194
-2.0	0.8	0.6289		13	3	SMBD 195
-2.0	0.4	0.7180		13	4	SMBD 196
-2.0	0.0	0.7457		13	5	SMBD 197
-2.0	-0.4	0.7180		13	6	SMBD 198
-2.0	-0.8	0.6		13	7	SMBD 199
-2.0	-1.2	0.4		13	8	SMBD 200
-2.0	-1.4907	0.0		13	9	SMBD 201
-2.0	-1.322	-0.3444		13	10	SMBD 202
-2.0	-0.8	-0.6289		13	11	SMBD 203
-2.0	-0.4	-0.7180		13	12	SMBD 204
-2.0	0.0	-0.7454		13	13	SMBD 205
-2.0	0.4	-0.7180		13	14	SMBD 206
-2.0	0.8	-0.6289		13	15	SMBD 207
-2.0	1.322	-0.3444		13	16	SMBD 208
-2.0	1.4907	0.0		13	17	SMBD 209
-2.5	1.055	0.6	1	14	1	SMBD 210
-2.5	1.0	0.2357		14	2	SMBD 211
-2.5	0.8	0.3815		14	3	SMBD 212
-2.5	0.4	0.5153		14	4	SMBD 213
-2.5	0.0	0.5528		14	5	SMBD 214
-2.5	-0.4	0.5153		14	6	SMBD 215
-2.5	-0.8	0.3815		14	7	SMBD 216
-2.5	-1.0	0.2357		14	8	SMBD 217
-2.5	-1.055	0.0		14	9	SMBD 218
-2.5	-1.0	-0.2357		14	10	SMBD 219
-2.5	-0.8	-0.3815		14	11	SMBD 220
-2.5	-0.4	-0.5153		14	12	SMBD 221
-2.5	0.0	-0.5528		14	13	SMBD 222
-2.5	0.4	-0.5153		14	14	SMBD 223
-2.5	0.8	-0.3815		14	15	SMBD 224

-2.5	1.0	-0.2357		14	16	SMBD 225
-2.5	1.055	0.0		14	17	SMBD 226
-2.5	1.055	0.0	2	15	1	SMBD 227
-2.5	0.8	0.3815		15	2	SMBD 228
-2.5	0.4	0.5153		15	3	SMBD 229
-2.5	0.0	0.5528		15	4	SMBD 230
-2.5	-0.4	0.5153		15	5	SMBD 231
-2.5	-0.8	0.3815		15	6	SMBD 232
-2.5	-1.055	0.0		15	7	SMBD 233
-2.5	-0.8	-0.3815		15	8	SMBD 234
-2.5	-0.4	-0.5153		15	9	SMBD 235
-2.5	0.0	-0.5528		15	10	SMBD 236
-2.5	0.4	-0.5153		15	11	SMBD 237
-2.5	0.8	-0.3815		15	12	SMBD 238
-2.5	1.055	0.0		15	13	SMBD 239
-3.0			1	16	1	SMBD 240
-3.0				16	2	SMBD 241
-3.0				16	3	SMBD 242
-3.0				16	4	SMBD 243
-3.0				16	5	SMBD 244
-3.0				16	6	SMBD 245
-3.0				16	7	SMBD 246
-3.0				16	8	SMBD 247
-3.0				16	9	SMBD 248
-3.0				16	10	SMBD 249
-3.0				16	11	SMBD 250
-3.0				16	12	SMBD 251
-3.0			3	16	13	SMBD 252

BOXC

Card No.						
1	TEST BODY				TFF	1 TEST
2						
4						
4A	2.0	2	1	1	SMBD	1
	2.0		1	2	SMBD	2
	2.0		1	3	SMBD	3

(See data card listing which follows the PBOXC input.)

FLOPNT

Card No.			
1	TEST		
2	TEST PROBLEM WITH TEST BODY		
3	1 3 2		
4	-4.5	1.	4
5	0.	0.	1
6	1.	-5	5
3			

ARYTRJ

Card No.

```
   1234567890123456789012345678901234567890123456789012345678901234567890123456789 0
1  TEST
2   TEST PROBLEM WITH TEST BODY
3  90.       1.0      .90925    268.659    0.
4   1.0
5  300.
6    3   1   2   2
7  -5.0      0.0           1
8  -1.0      2.0           2
9   1.0     -2.0           2
5
```

CONFAC

Card No.	
1	TEST
2	TEST PROBLEM WITH TEST BODY
3	90. 1. .90925 268.659 -5.
4	1.
5	4 .00328 .5
6	
7	
8	300.
9	-1.5 1.1 .8
8	

TANTRA

Card No.	1–10	11–20	21–30	31–40	41–50	51–60	61–70	71–80
1	TEST							
2	TEST PROBLEM WITH TEST BODY							T
3	90.	1.	.90925	268.659	0.			
4	1.							
5	200.							
6	.05	.005						
7	-5.	0.	-.45	-5.	0.	0.		
6								
5								

STEREO

Card No.	
1	PLOT TANGENT TRAJECTORY TO THE TEST BODY
2	T 1 -5.0
3	PLOT TANGENT TRAJECTORY TO THE TEST BODY
4	2/14/80
5	0. 160. 3.5
6	THETA=0, PSI=160, DELTA=3.5
5	0. 160. 3.0
6	THETA=0, PSI=160, DELTA=3.0
5	0. 160. 2.5
6	THETA=0, PSI=160, DELTA=2.5
5	
6	

Figure 9 shows a stereo pair of plots of the test body and the tangent trajectory calculated via the TANTRA test problem.

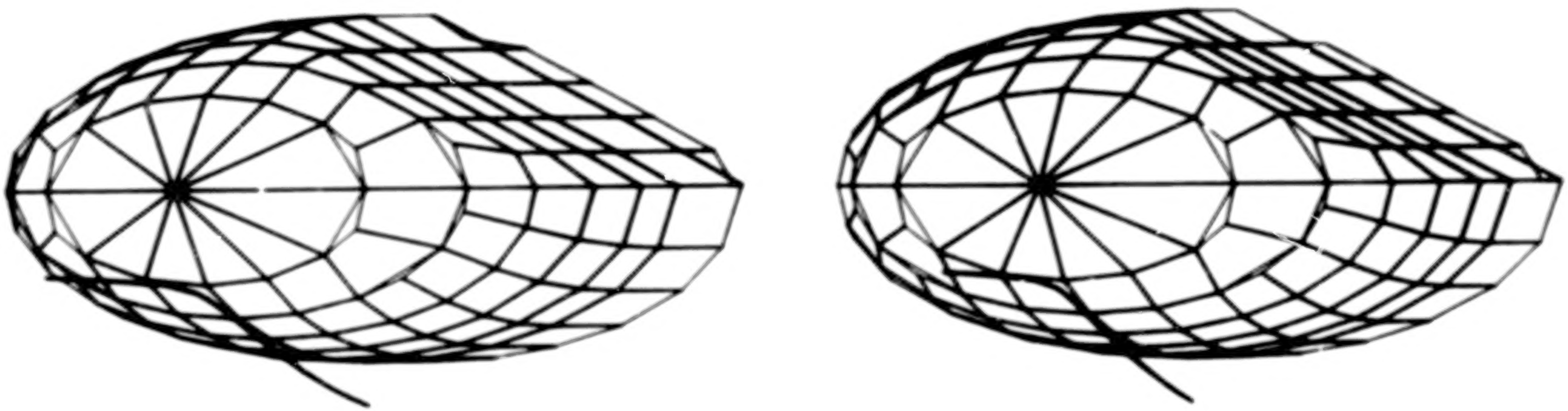

Figure 9. Stereographic plot of the tangent trajectory of a 200 μm diameter water drop to the lower side of the test body in the y = 0 plane. Plotted from the results of the TANTRA test problem. Three-dimensional perspective can be attained by staring at the center of the figure and then crossing the eyes such that the two images merge.

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15. Supplementary Notes

Final report. Project Manager, Robert J. Shaw, Propulsion Systems Division, NASA Lewis Research Center, Cleveland, Ohio 44135. The microfiche supplement at the back of this report contains an example problem printout and code listings.

16. Abstract

Calculations can be performed for any atmospheric conditions and for all water drop sizes, from the smallest cloud droplet to large raindrops. Any subsonic, external, non-lifting flow can be accommodated; flow into, but not through, inlets also can be simulated. Experimental water drop drag relations are used in the water drop equations of motion and effects of gravity settling are included. Seven codes are described: 1. a code used to debug and plot body surface description data, 2. a code that processes the body surface data to yield the potential flow field, 3. a code that computes flow velocities at arrays of points in space, 4. a code that computes water drop trajectories from an array of points in space, 5. a code that computes water drop trajectories and fluxes to arbitrary target points, 6. a code that computes water drop trajectories tangent to the body, 7. a code that produces stereo pair plots which include both the body and trajectories. Code descriptions include operating instructions, card inputs and printouts for example problems, and listings of the FORTRAN codes. Accuracy of the calculations is discussed, and trajectory calculation results are compared with prior calculations and with experimental data.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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